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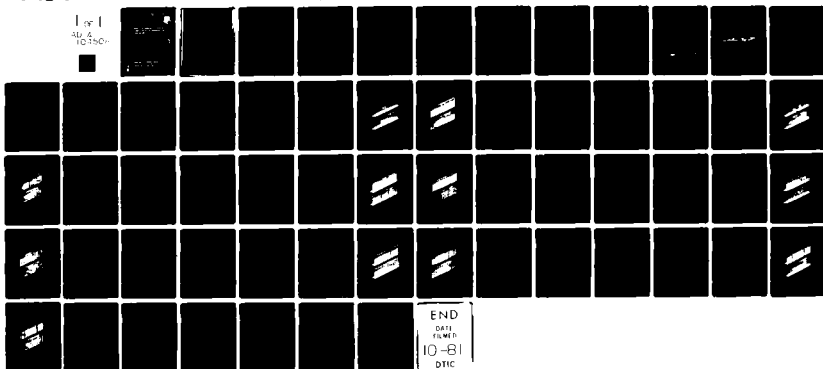
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In-House Report

October 1980



## EFFECTS OF ENERGETIC PARTICLE EVENTS ON VLF/LF PROPAGATION PARAMETERS, 1974-1977

John P. Turtle  
John E. Rasmussen  
Wayne I. Klemetti

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EDWARD A. LEWIS, Chief  
Propagation Branch  
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| 1. REPORT NUMBER<br>RADC-TR-80-307   | 2. GOVT ACCESSION NO.<br>AD-A204508 | 3. RECIPIENT'S CATALOG NUMBER  |
| 4. TITLE (and Subtitle)<br>EFFECTS OF ENERGETIC PARTICLE EVENTS<br>ON VLF/LF PROPAGATION PARAMETERS, ---<br>1974-1977  |                                     | 5. TYPE OF REPORT & PERIOD COVERED<br>In-House                                       |
| 6. AUTHOR(s)<br>John P. Turtle<br>John E. Rasmussen<br>Wayne L. Klemetti   |                                     | 6. PERFORMING ORG. REPORT NUMBER   |
| 7. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Deputy for Electronic Technology (RADC/EEPL)<br>Hanscom AFB<br>Massachusetts 01731  |                                     | 8. CONTRACT OR GRANT NUMBER(s)   |
| 9. CONTROLLING OFFICE NAME AND ADDRESS<br>Deputy for Electronic Technology (RADC/EEPL)<br>Hanscom AFB<br>Massachusetts 01731   |                                     | 10. PROGRAM ELEMENT, PROJECT, TASK<br>AREA & WORK UNIT NUMBERS<br>62702F<br>46001604 |
| 11. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)  |                                     | 12. REPORT DATE<br>October 1980  |
|  |                                     | 13. NUMBER OF PAGES<br>68  |
|  |                                     | 14. SECURITY CLASS. (of this report)<br>Unclassified                                 |
|  |                                     | 15. DECLASSIFICATION DOWNGRADING<br>SCHEDULE   |
| 16. DISTRIBUTION STATEMENT (of this Report)<br><br>Approved for public release; distribution unlimited.  |                                     |  |
| 17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)   |                                     |  |
| 18. SUPPLEMENTARY NOTES<br><br>*Megapulse Inc., Bedford, MA  |                                     |  |
| 19. KEY WORDS (Continue on reverse side if necessary and identify by block number)<br>VLF propagation<br>LF propagation<br>Ionospheric disturbances<br>Polar cap absorption events   |                                     |  |
| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br>This report provides a summary of disturbance effects of energetic particle events on VLF/LF propagation parameters as observed by the USAF High Resolution VLF/LF Ionosounder in Northern Greenland. Disturbance effects on ionospheric reflectivity parameters, including reflection heights and coefficients, are presented along with data from a riometer, a magnetometer, and satellite particle detectors. |                                     |  |

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## Preface

The authors thank Royce C. Kahler and Duane Marshall for help with the instrumentation which made the measurements possible, and Jens Ostergaard and Bjarne Ebbesen for the outstanding operation in *Qanaq, Greenland*.

Appreciation is also extended to the Danish Commission for Scientific Research in Greenland for allowing these measurements to be conducted, and to Jorgen Taagholt and V. Neble Jensen of the Danish Meteorological Institute's Ionospheric Laboratory for their continued cooperation in this program.

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## Effects of Energetic Particle Events on VLF/LF Propagation Parameters, 1974-1977

### 1. INTRODUCTION

A compilation of data on the VLF/LF reflectivity of the polar ionosphere from 1975 to 1977 has been published in previous technical reports.<sup>1-10</sup> In this report, the data for specific periods are expanded in order to give a more detailed presentation of the effects of energetic particle events on VLF/LF propagation parameters. These periods have been chosen to show disturbance effects for events in which the 13.7 to 25.2 - MeV proton flux recorded by the IMP 7/8 satellites exceeded  $10^{-2}$  particles/cm<sup>2</sup> sec sr MeV. The propagation data were obtained by the USAF High Resolution VLF/LF Ionosounder<sup>11, 12</sup> which provides direct measurements of ionospheric reflection height and the reflection coefficient matrix elements  $||R_{||}$  and  $||R_{\perp}$ .<sup>13</sup> Also included are data on particle flux density, HF riometer absorption, and geomagnetic field intensity.

(Received for publication 6 October 1980.)

Due to the number of references cited on this page, the reader is directed to pages 67 and 68 for references 1 through 10.

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The VLF/LF Ionosounding Transmitter (Figure 1) is located at Thule Air Base, Greenland (76° 33' N Lat., 68° 40' W Long.), and the receiving site is 106 km north at the Danish Meteorological Institute's Ionospheric Observatory in Qanaq, Greenland (77° 24' N Lat., 69° 20' W Long., Geomagnetic Lat. 89° 06' N). The ionosounding transmissions consist of a series of extremely short (approximately 100  $\mu$ sec) VLF pulses, precisely controlled in time, and radiated from the 130-m vertical antenna (Figure 2). At the receiver, the radiated signal arrives first by groundwave propagation (Figure 3). Due to the extremely short pulse length, this signal has passed the receiver before the arrival of the ionospherically reflected skywave pulse, providing independent groundwave and skywave data. Orthogonal loop antennas (Figure 4) are used to receive the two polarization components of the ionospherically reflected skywave signal. One loop, oriented in the plane of propagation, senses the groundwave and the unconverted or "parallel" (||) component of the down-coming skywave; the second loop, nulled on the groundwave, senses the converted or perpendicular ( $\perp$ ) skywave component. The signal from each of the antennas is digitally averaged to improve the signal-to-noise ratio of the individual received waveforms before they are recorded on magnetic tape. An example of the observed waveforms is given in Figure 5, where the parallel waveform (a) consists of a groundwave propagated pulse, a quiet interval containing low level, off path groundwave reflections, followed by the first-hop parallel skywave component; the perpendicular waveform (b) is also shown. Each of these waveforms is comprised of 256 digitally averaged points, spaced 2  $\mu$ sec apart. Ionospheric reflection parameters are derived by computer processing of the ground and ionospherically reflected waveforms, with allowance made for factors such as ground conductivity and antenna patterns (see Section 2.2).

On 25 September 1975, and on 1 May 1977, the transmitted waveform was changed slightly; Figure 6 shows the resulting effect on the Fourier amplitude spectrum of the received groundwave signal. Although the data presented are generally limited to frequencies in the first, or principal lobe of the spectrum, information at higher frequencies can be used when sufficient signal-to-noise conditions exist. There is, however, a frequency range around each spectral null where insufficient signal exists for measurements.

## 2. EVENT DATA

The data are presented for each disturbance event in three general formats: first, the observed waveforms are shown in a synthetic three-dimensional display which starts approximately two days prior to the event and covers a fourteen-day period; second, the data are presented in the frequency domain with reflection

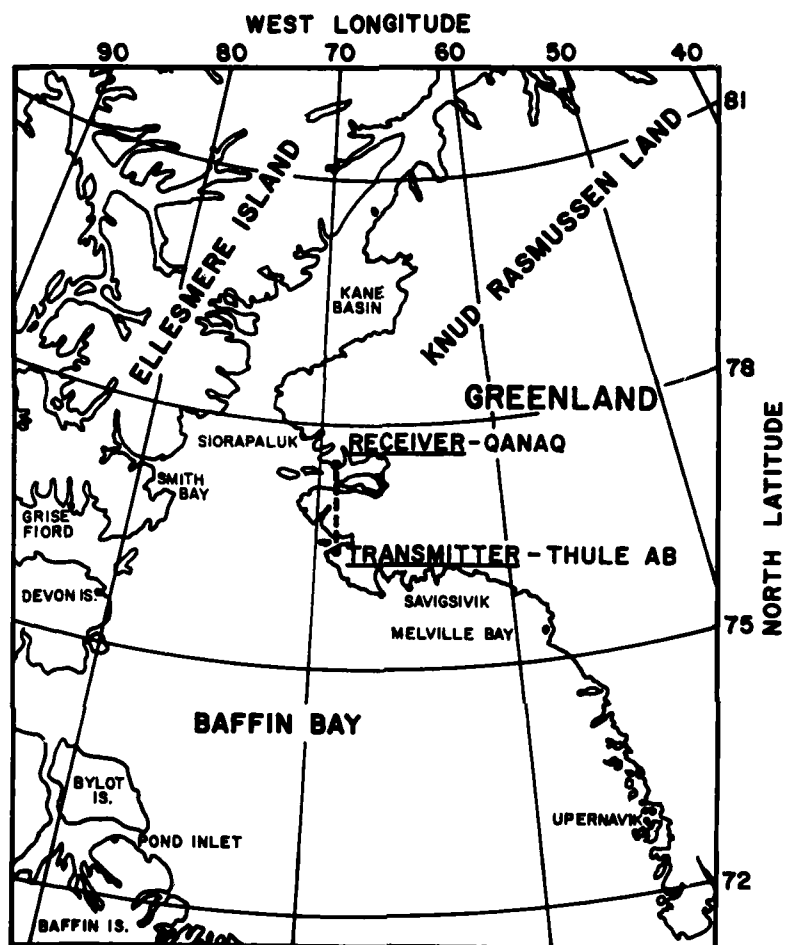


Figure 1. Ionosounder Propagation Path, Thule AB - Qanaq, Greenland

Figure 2. Transmitting Antenna,  
Thule AB - Qanaq, Greenland

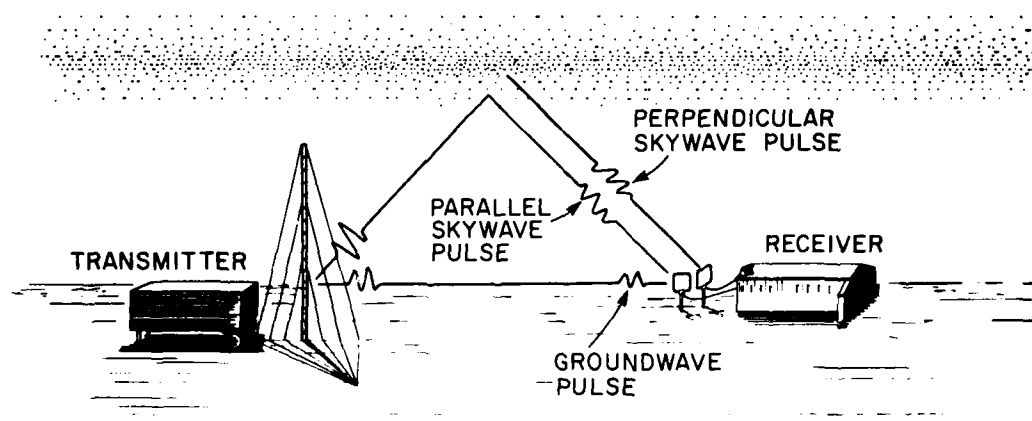


Figure 3. Basic Ionosounding Experiment

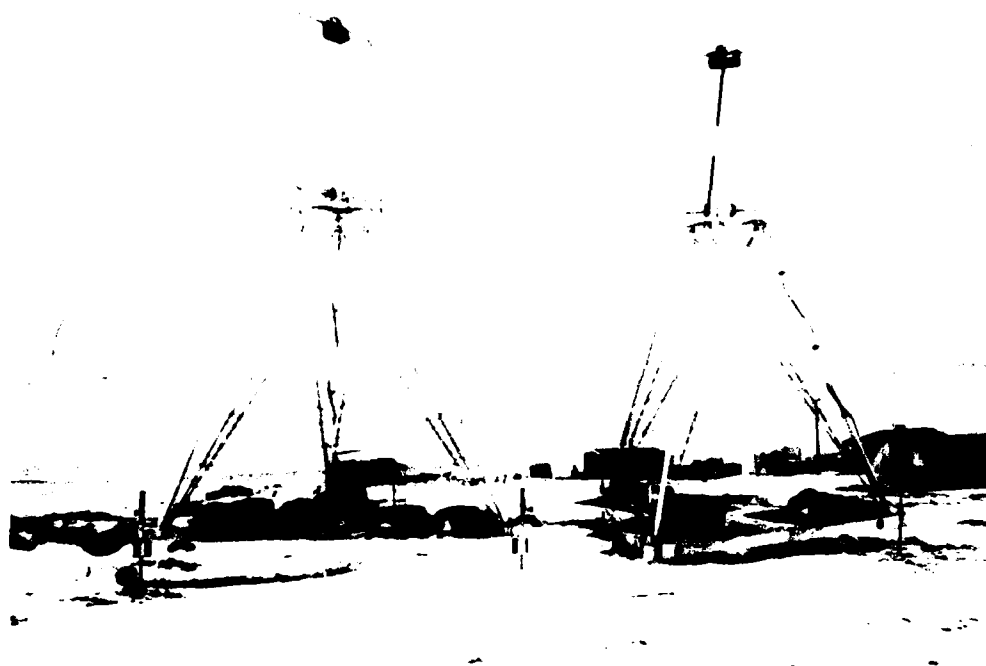


Figure 4. Orthogonal Receiving Antennas, Qanaq, Greenland

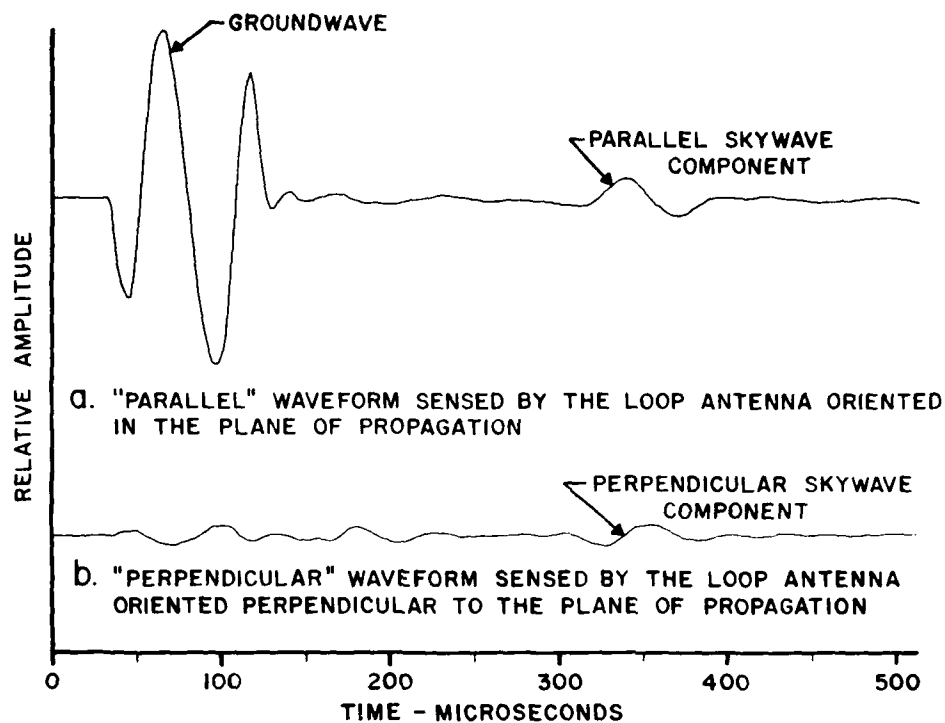


Figure 5. Example of Parallel and Perpendicular Waveforms

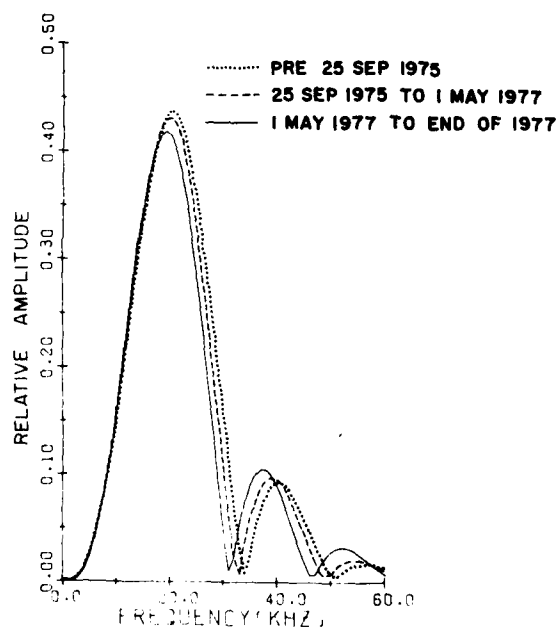


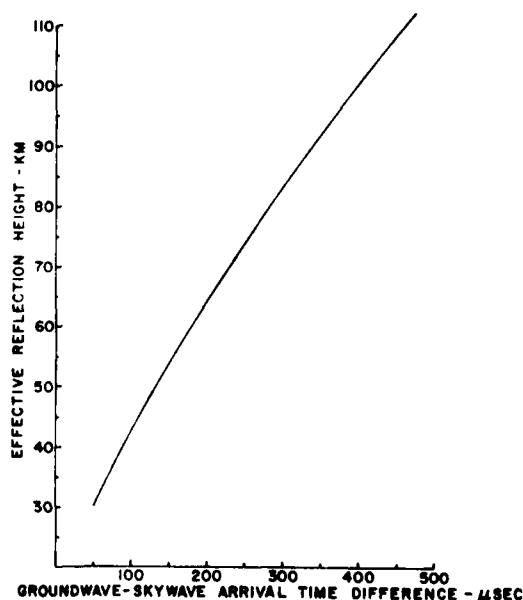
Figure 6. Fourier Amplitude Spectrum of Transmitted Pulse

heights and coefficients plotted as a function of frequency over the range from approximately 5 to 30 kHz; third, the data are presented as a function of time-of-day. In addition to reflection information, this section contains data on ionospheric absorption, geomagnetic field data activity, and solar proton fluxes.

## 2.1 Observed Waveforms

A three-dimensional waveform display is presented for a 2-week period containing each disturbance event, together with a display of the same 2-week period from a year in which it was not disturbed. For each display, the waveforms were stacked one behind the other in linear time, progressing from bottom to top. Each individual waveform is a 30-min average of approximately 10,000 pulses. The horizontal scale for these plots is linear in time (microseconds), measured from the start of the groundwave. This scale can be used to calculate an effective height of reflection by attributing the time delay between the start of the groundwave and the start of the skywave to a difference in travel distance, assuming a sharply bounded, mirror-like ionosphere. Figure 7 gives a conversion curve for this calculation based on simple geometry and the specific Thule AB - Qanaq, Greenland separation of 106 km. For the disturbance periods, fixed local ground clutter, amounting to only 2 percent of the groundwave amplitude, was removed to avoid interference with the skywave and improve the appearance of the waveforms.

Figure 7. Conversion Curve, Groundwave-Skywave Arrival Time Difference to Reflection Height



The three-dimensional displays of the disturbed and normal parallel waveforms are given for each event in Parts A and B of Figures 8 through 13. A plot of the diurnal variation in solar zenith angle for the midpoint of the path appears in Part C. The perpendicular waveform displays are shown in Parts D and E. The time of maximum particle flux is indicated on the disturbance plots.

## 2.2 Quantitative Parallel and Perpendicular Reflection Parameters

For each event individual parallel and perpendicular waveforms were selected in order to show the effects of the disturbance on the ionospheric reflection height and reflection coefficients as a function of frequency. The selected waveforms from the disturbance period are shown in Part F of the data figures, whereas the corresponding undisturbed waveforms are shown in Part G.

### 2.2.1 REFLECTION HEIGHTS

The group mirror height (GMH) of reflection was obtained by determining the group delay of the skywave relative to the groundwave and attributing this difference to a difference in the propagation distance. The group delay can be defined as the rate of change of phase with frequency as discussed in Lewis et al.<sup>11</sup> For the GMH data presented in this report, a finite frequency difference of 1.0 kHz was used, and the corresponding phase difference as a function of frequency for the groundwave and both skywave signals was obtained by Fourier analysis of the respective pulses. The GMH calculations took into account ground conductivity ( $10^{-3}$  mho/m is assumed), with the Wait and Howe<sup>14</sup> corrections applied. Group mirror heights for the parallel and perpendicular waveforms are plotted as a function of frequency in Parts H and I of Figures 8 through 13 for both normal and disturbed conditions. The GMHs are also presented as a function of time-of-day for the average frequency of 16.5 kHz. In Figures 8 through 13, Parts L and O, parallel and perpendicular reflection height information is given based on two-hour averaged data for the two-week period; Parts V and W show the 24-hour period of the event onset in greater detail, based on 5-min averaged data. These parts include a normal reflection height curve for reference purposes. Each point of the reference height curve is an average, by two-hour time blocks, for the 14-day normal period indicated.

### 2.2.2 REFLECTION COEFFICIENTS

Assuming that the ionosphere acts as a "mirror" at the GMH, we obtained plane wave reflection coefficients<sup>13</sup> by comparing the ratio of the skywave Fourier amplitude at a specific frequency to that of the groundwave, taking into account the

14. Wait, J. R. and Howe, H. H. (1956) Amplitude and Phase Curves for Ground-wave Propagation in the Band 200 Cycles per Second to 500 Kilocycles, Natl. Bureau of Standards, U. S. Circ. No. 574.

wave spreading, earth curvature, ground conductivity, path lengths, and antenna patterns including ground image effects.

The reflection coefficient  $||R_{||}$ , obtained from analysis of the parallel sky-wave component, is plotted as a function of frequency for both normal and disturbed conditions in Part H. From the corresponding perpendicular skywave pulses, the coefficient  $||R_{\perp}$  was obtained; it appears as a function of frequency in Part I. The  $||R_{||}$  coefficient for 16 kHz is plotted as a function of time-of-day in Part M along with the averaged normal coefficient. As with the reflection heights, a more detailed  $||R_{||}$  coefficient plot, based on 5-min averaged data is shown in Part V. To show the variation in reflectivity as a function of frequency during the event, the reflection coefficients were calculated at 8 kHz, 16 kHz, and 22 kHz and are plotted in Part N as a function of time for the 14-day period. The corresponding reflection coefficient plots for  $||R_{\perp}$  are given in Parts P, Q, and W.

For certain coefficient data points, plotted as asterisks, the reflection coefficient appears without a corresponding GMH. For these particular data, only the skywave-groundwave ratios could be obtained since the skywaves were too weak to provide reliable group delay information. The reflection coefficients were estimated using a nominal GMH of 80 km in the calculations. These estimated coefficient values are included in the averages presented in Parts M, N, P, and Q, but the assumed heights are not used in the GMH averages.

### 2.3 Polarization Ellipses for the Down-Coming Skywaves

As described by Rasmussen et al,<sup>15</sup> the polarization ellipse of the skywave can be determined from the amplitudes of the parallel and perpendicular components and their phase difference. Each ellipse represents the locus of the tip of the rotation field vector as seen when looking in the direction of propagation of the down-coming skywave. The ellipses are drawn to a scale in which the incident wave amplitude is unity, and each division on the axis is 0.1. The direction of rotation is indicated by an arrow. Parts J and K of Figures 8 through 13 present polarization ellipse data as a function of frequency at 5 kHz intervals based on the selected disturbed and normal waveforms of Parts F and G, respectively.

## 3. SUPPLEMENTARY DATA

In order to interpret the effects of ionospheric disturbances on the VLF/LF ionosounding data, information from several geophysical sensors is presented. Parts R and S of Figures 8 through 13 present data from a magnetometer and a

15. Rasmussen, J. E., et al., (1975) Low Frequency Wave-Reflection Properties of the Equatorial Ionosphere, AFCRL-TR-75-0615.



30-MHz riometer operated by RADC at Thule Air Base. The riometer, the conventional monitor of ionospheric disturbances, measures the signal level of cosmic radio noise passing through the ionosphere. The cyclical diurnal variation seen in the riometer signal level during undisturbed periods is caused primarily by the earth's daily rotation with respect to the extraterrestrial noise sources. A decrease in the received noise level represents an increase in the absorption resulting from enhanced ionization due to energetic particles. The absorption effects of energetic particle events are seen as an abrupt decrease in the riometer signal level followed by a gradual recovery to normal over a period of several days. The magnetometer data plotted are the horizontal (H) component of the polar magnetic field determined by a 3-axis fluxgate magnetometer at Thule Air Base. The magnetometer responds to the effects of polar ionospheric current systems related to disturbance events.

In addition to the information from the ground-based monitors, particle flux data are presented from the Applied Physics Laboratory of Johns Hopkins University experiments aboard the IMP 7 and 8 satellites.\* These satellites are in roughly circular orbits at about 35 earth radii. The data presented in Parts T and U are hourly averages of differential flux levels for protons in two energy ranges: 0.97 to 1.85 MeV and 13.7 to 25.2 MeV. These particle data are most important for relating the VLF/LF ionosounder effects to the size of a particular disturbance.

The supplementary data are summarized in Table 1.

Table 1. Disturbance Event Data

| Date                  | Maximum<br>13.7-25.2 MeV<br>Protons/cm <sup>2</sup><br>sr sec MeV | Minimum<br>16 kHz II<br>Reflection<br>Height (km) | 30 MHz<br>Riometer (dB)<br>Absorption | Illumination<br>Conditions |
|-----------------------|---|---|---------------------------------------|----------------------------|
| 5 Nov 74<br>Day 309   | 1.3   | 63  | <0.5                                  | nighttime                  |
| 30 Apr 76<br>Day 121  | 6   | 58  | 3                                     | daytime                    |
| 22 Aug 76<br>Day 235  | 0.6   | 60  | 1.7                                   | daytime                    |
| 26 July 77<br>Day 207 | 0.02  | 70  | <0.5                                  | daytime                    |
| 24 Sep 77<br>Day 267  | 2   | 57  | 2                                     | daytime                    |
| 22 Nov 77<br>Day 326  | 14  | 64  | 0.75                                  | nighttime                  |

\*Particle data obtained from the National Space Science Data Center, Greenbelt, MD

#### 4. DISTURBANCE CHARACTERISTICS

From the events included in this report, the following VLF/LF disturbance patterns can be seen in the ionosounding data. The reflection heights for both the parallel and perpendicular components drop coincident with the influx of energetic particles. The level to which the reflection heights drop depends first, upon the magnitude of the particle flux, and second, upon the presence or absence of solar illumination during the event. The lowest reflection heights for a given particle flux are attained during a daytime event. As seen in Table 1, the 22 Aug 76 (DOY 235) polar daytime event with a 13 to 25 MeV proton flux of 0.6 particles resulted in a 16-kHz reflection height of 60 km; whereas the more energetic 22 Nov 77 (DOY 326) polar nighttime event with flux of 14 particles caused a drop in reflection height to only 64 km. During polar daytime events with continuous D-region illumination, there is little if any diurnal height variation even if there are variations before and after the event. During polar nighttime events, a combination of particle ionization and weak noontime solar illumination can produce a diurnal variation during the event when none was present before or even after. For day-night events with the sun rising and setting, the disturbed reflection heights show a strong diurnal pattern, sometimes with larger variations than either before or after the event.

Reflection coefficients during energetic particle disturbances also behave differently, depending upon the solar illumination conditions. During a normal polar daytime period, with the sun continually above the horizon, reflection coefficients are quite variable and much lower than during a normal nighttime period. During a daytime particle event, reflection coefficients can actually increase with respect to normal conditions, particularly for 8 and 16 kHz. The coefficients show less diurnal variation during the event since the effects of particle ionization appear to override the effects of varying solar zenith angle. For the two strong daytime events, 30 Apr 76 (DOY 122) and 22 Aug 76 (DOY 235), several days after event maximum, the ionospherically reflected pulse became very weak for a period of approximately one day, resulting in reduced reflection coefficients before returning to normal conditions. This behavior is not associated with additional particle precipitation; it may be a part of the daytime recovery process for the particular geometry of the Thule AB - Qanaq path. Reflection coefficient behavior for nighttime and day-night disturbances is less complex, and similar in pattern to the reflection heights. During a polar nighttime event, the reflection coefficients decrease coincident with the particle influx and then recover steadily to normal. During day-night disturbed conditions, the reflection coefficients show an enhanced diurnal variation compared with variations prior to and following the event.

### 5 November 1974 Solar Particle Event

Date: 5 November 1974    DOY: 309  
Report Figure: 8  
Related Solar Flare: 5 November 1530 UT  
Start of Ionospheric Effects: 1600 UT  
Time of Maximum 13-25 MeV Proton Flux: 2200 UT  
Maximum Flux: 1.3 particles/cm<sup>2</sup> sec sr MeV  
Length of Particle Event: 3 days  
Lowest Reflection Height (16 kHz): 63 km  
Time of Lowest Height: 1730 UT  
30 MHz Riometer Absorption: 0.5 dB  
Solar Zenith Angle Range: 93° - 121°  
Illumination Conditions: nighttime

Typical of polar nighttime conditions, before the event the  $R_{16}$  16 kHz ionospheric reflection coefficient was large (0.5) and the reflection height high (85 km). The disturbance effects on the propagation parameters were quite clear: a rapid decrease followed by a gradual return to normal. As seen in Parts L-Q, before the event there was little diurnal variation in the parameters due to insufficient noontime ionizing radiation. During the event, however, an enhanced variation is noted; this was probably due to a combination of particle ionization, and a small amount of noontime solar radiation.

It is probable that a small particle event occurred between 12 and 14 November (DOY 316-318). This can be seen in the reflection height and coefficient data in Parts L-Q, as well as in the particle and magnetometer data in Parts R and U.

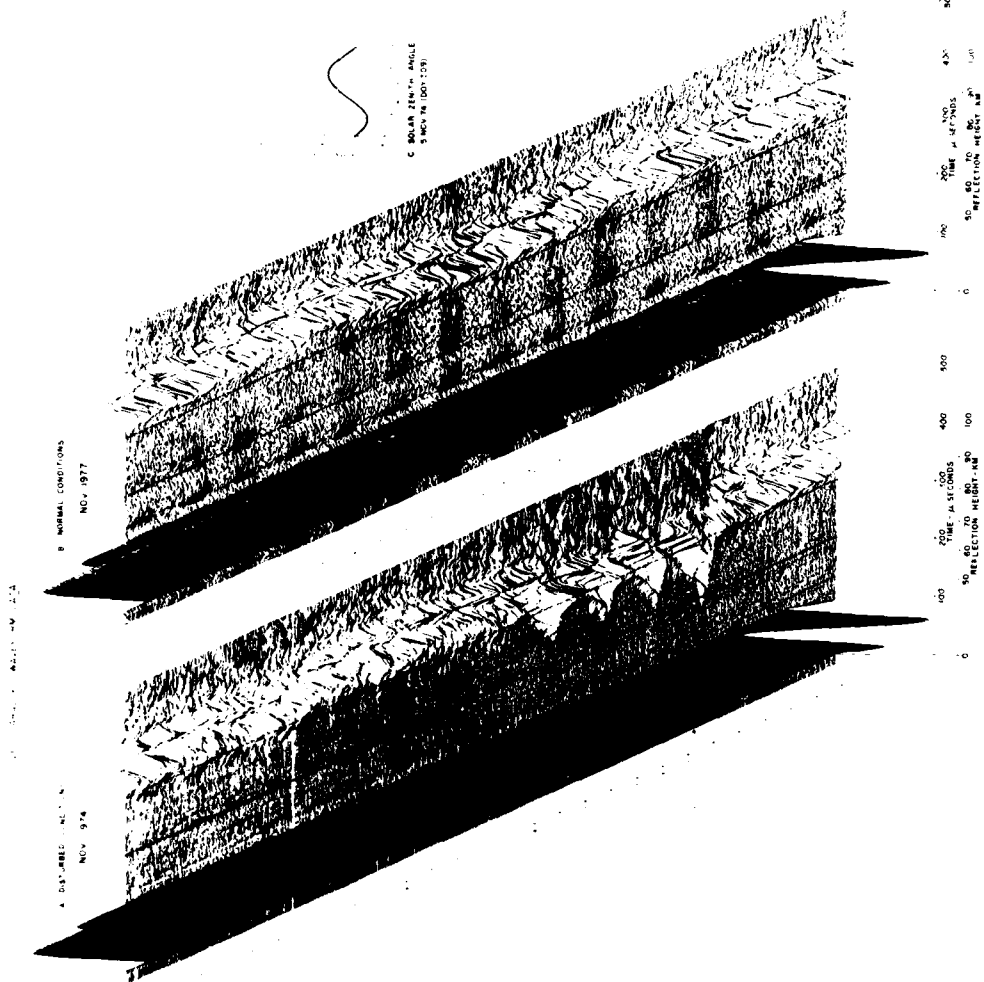


Figure 8. VLF/LF Ionospheric Reflectivity Data for 5 November 1974 (DON 309) Solar Particle Event (continued)

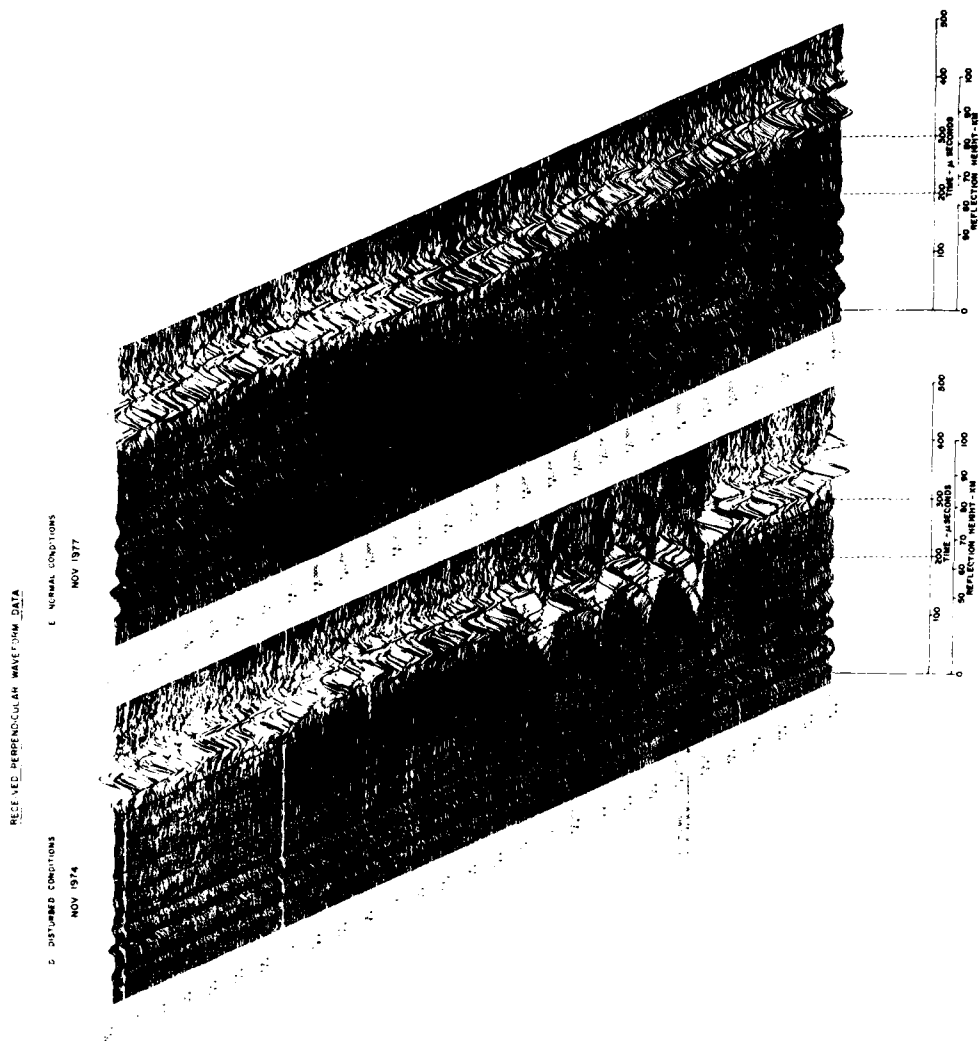


Figure 8. VLF/LF Ionospheric Reflectivity Data for 5 November 1974 (DOY 309) Solar Particle Event (continued)

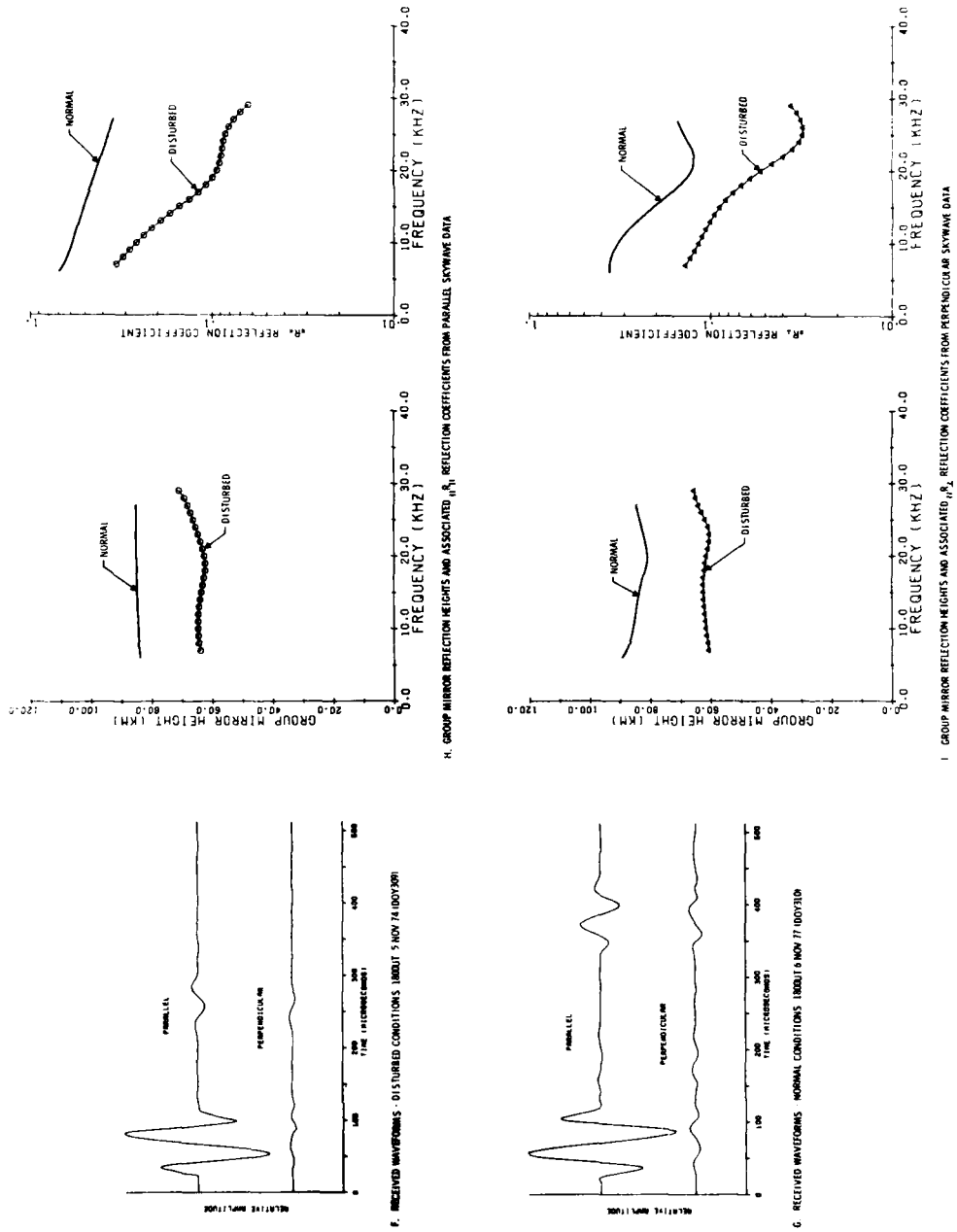
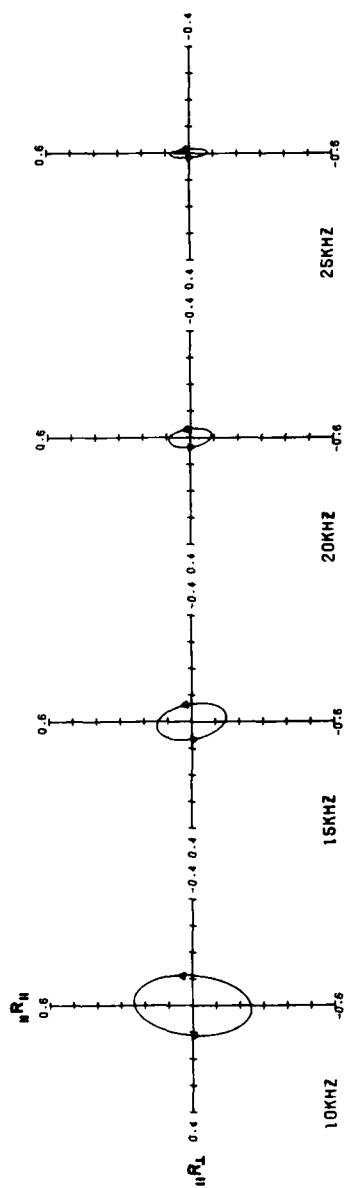
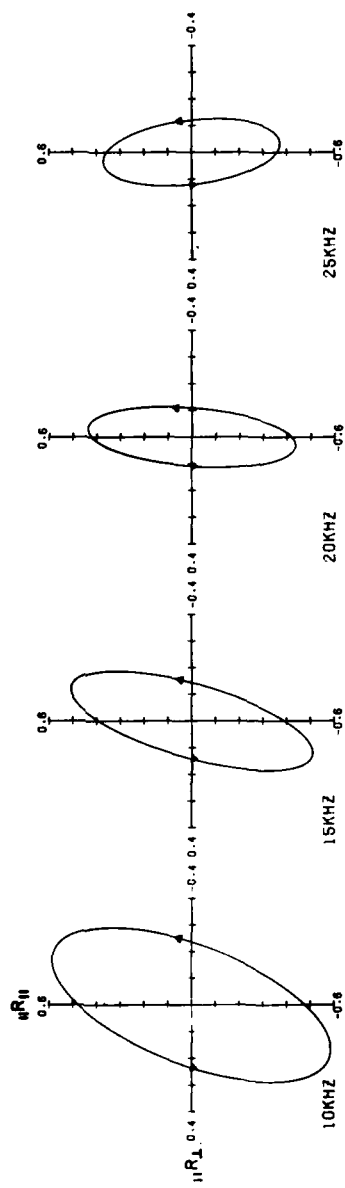


Figure 8. VLF/LF Ionospheric Reflectivity Data for 5 November 1974 (DOY 309) Solar Particle Event (continued)



J. SKYWAVE POLARIZATION ELLIPSES - DISTURBED CONDITIONS



K. SKYWAVE POLARIZATION ELLIPSES - NORMAL CONDITIONS

Figure 8. VLF/LF Ionospheric Reflectivity Data for 5 November 1974 (DON 309) Solar Particle Event (continued)

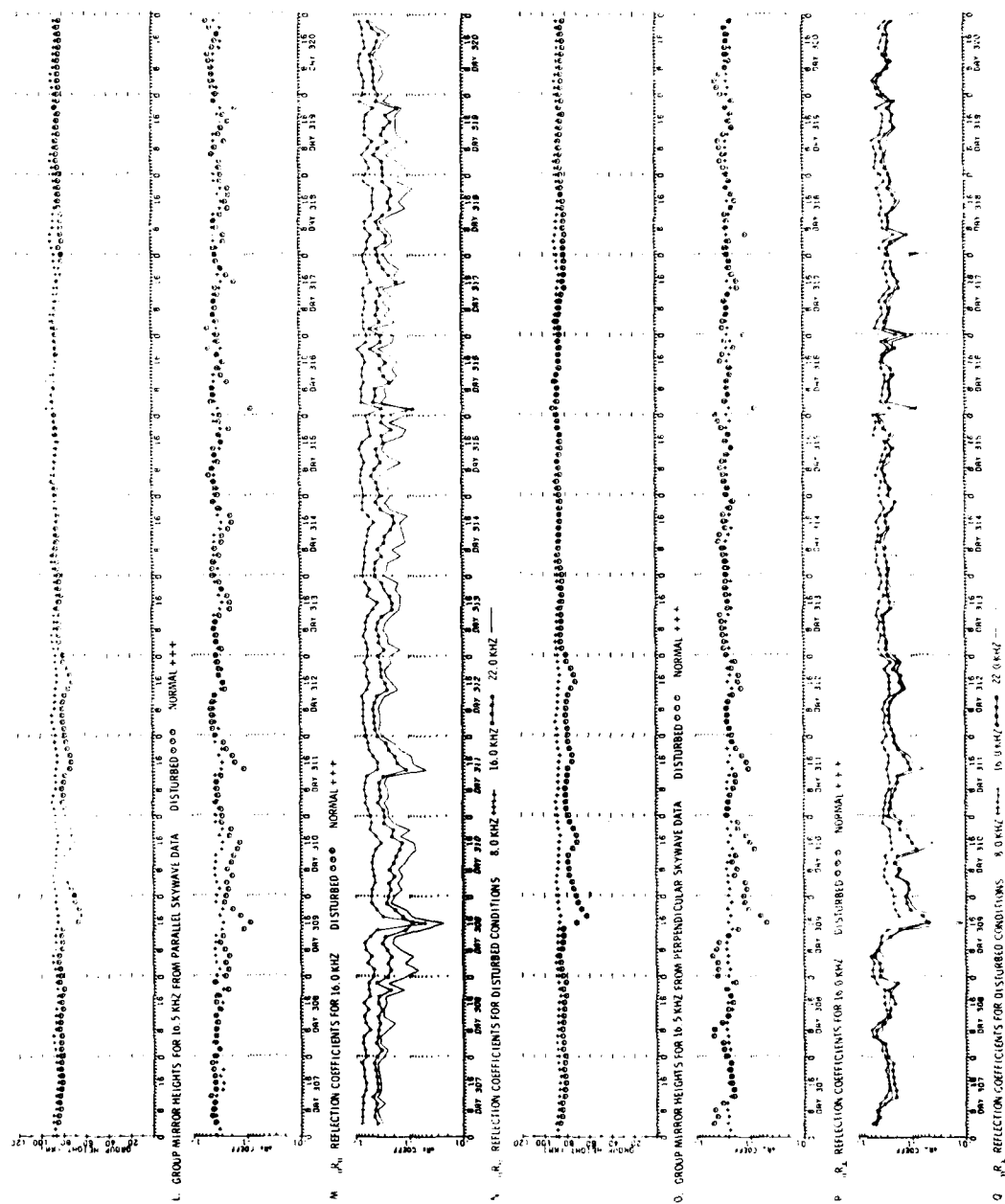


Figure 8. VLF/LF Ionospheric Reflectivity Data for 5 November 1974 (DOY 309) Solar Particle Event (continued)



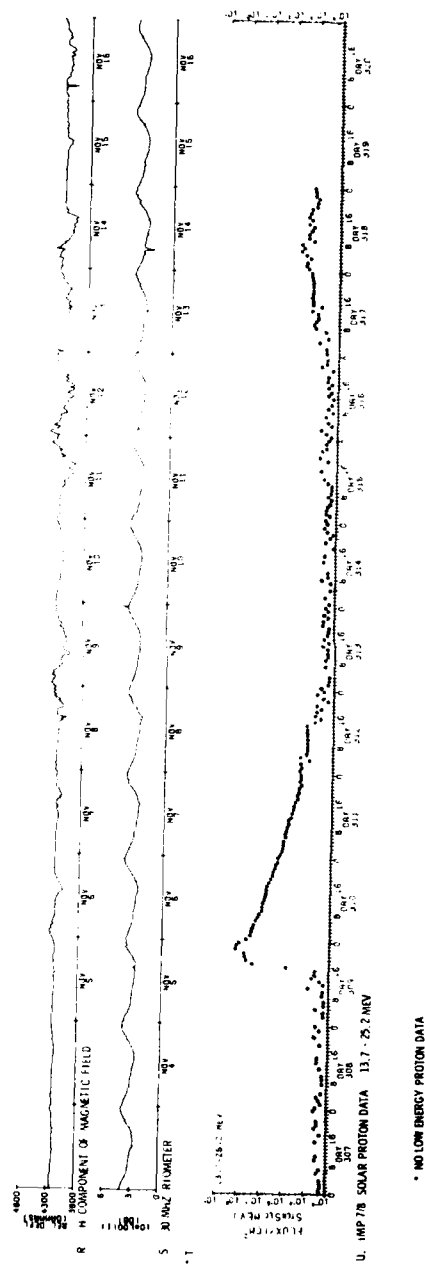


Figure 8. VLF/LF Ionospheric Reflectivity Data for 5 November 1974 (DOY 309) Solar Particle Event (continued)

### 30 April 1976 Solar Particle Event

Date: 30 April 1976 DOY: 121  
Report Figure: 9  
Related Solar Flare: 30 April 1976 UT x-ray class: X2  
Start of Ionospheric Effects: 2050 UT  
Time of Maximum 13-25 MeV Proton Flux: 1 May 0300 UT  
Maximum Flux: 6 particles/cm<sup>2</sup> sec sr MeV  
Length of Particle Event: 5 days  
Lowest 16 kHz Reflection Height: 58 km  
Time of Lowest Reflection Height: 1 May 0015 UT  
30 MHz Riometer Absorption: 3.5 dB  
Solar Zenith Angle Range: 63°-91°  
Illumination Conditions: daytime

As is typical of normal daytime conditions the  $R_{16}$  16 kHz reflection coefficients (Part H) were much lower (0.08) than during normal polar nighttime conditions (0.5). The effects of the disturbance on the reflection coefficients were less clearly defined than during a nighttime event. As seen in Part N, the parallel reflection coefficient showed an increase during the first part of the event. This was followed by a relatively stable period with little diurnal variation for the next two days. On 3 May (DOY 124), two days after event particle maximum, the reflected skywave pulse became very weak for about a day (Parts A and D). This is seen in the reflection coefficients in Parts N and Q which were lower on 3 May than during event maximum, particularly for 16 and 22 kHz. This was not related to an increase in particle flux, but may be part of the recovery process as associated with the particular geometry of the Thule Air Base - Qanaq path. Subsequent to 3 May, there was a gradual recovery over the next four days. The reflection heights during the event followed the usual pattern of abrupt drop followed by a gradual recovery; there was no diurnal height variation during this daytime event. The reflection heights returned to normal on 3 May (DOY 124), several days before the reflection coefficients.

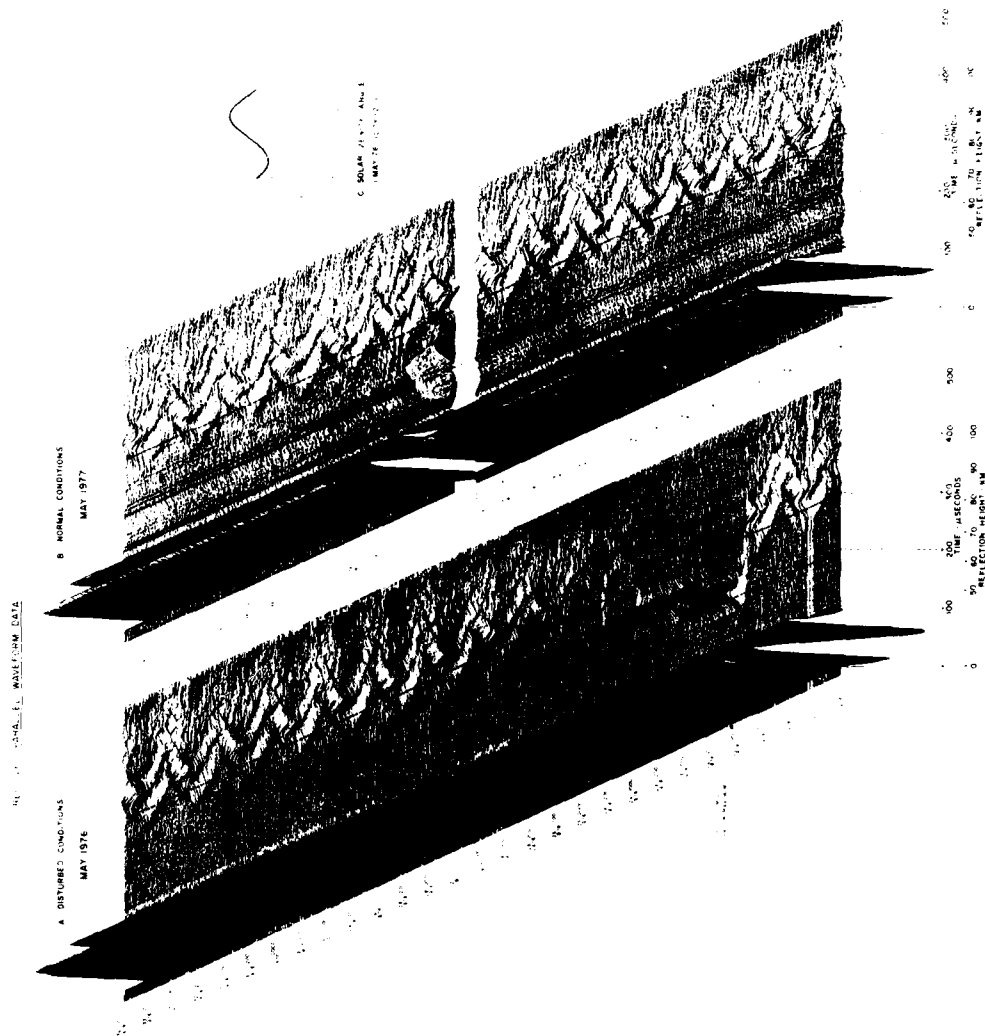
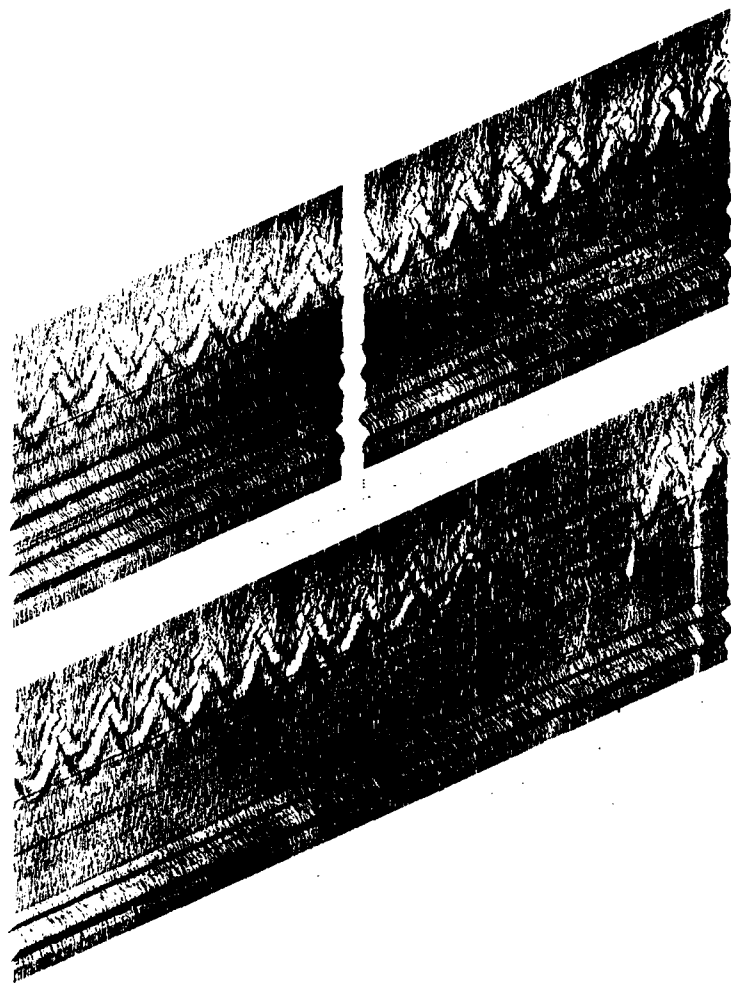


Figure 9. VLF/LF Ionospheric Reflectivity Data for 30 April 1976 (DOY 121) Solar Particle Event (continued)

REFLECTIVITY DATA FOR 30 APRIL 1976

TIME: 00:00  
LAT: 00  
LONG: 00

TIME: 00:00  
LAT: 00  
LONG: 00



TIME: 00:00  
LAT: 00  
LONG: 00  
REFLECTIVITY DATA FOR 30 APRIL 1976

Figure 9. VLF/LF Ionospheric Reflectivity Data for 30 April 1976 (000 121) Solar Particle Event (continued)

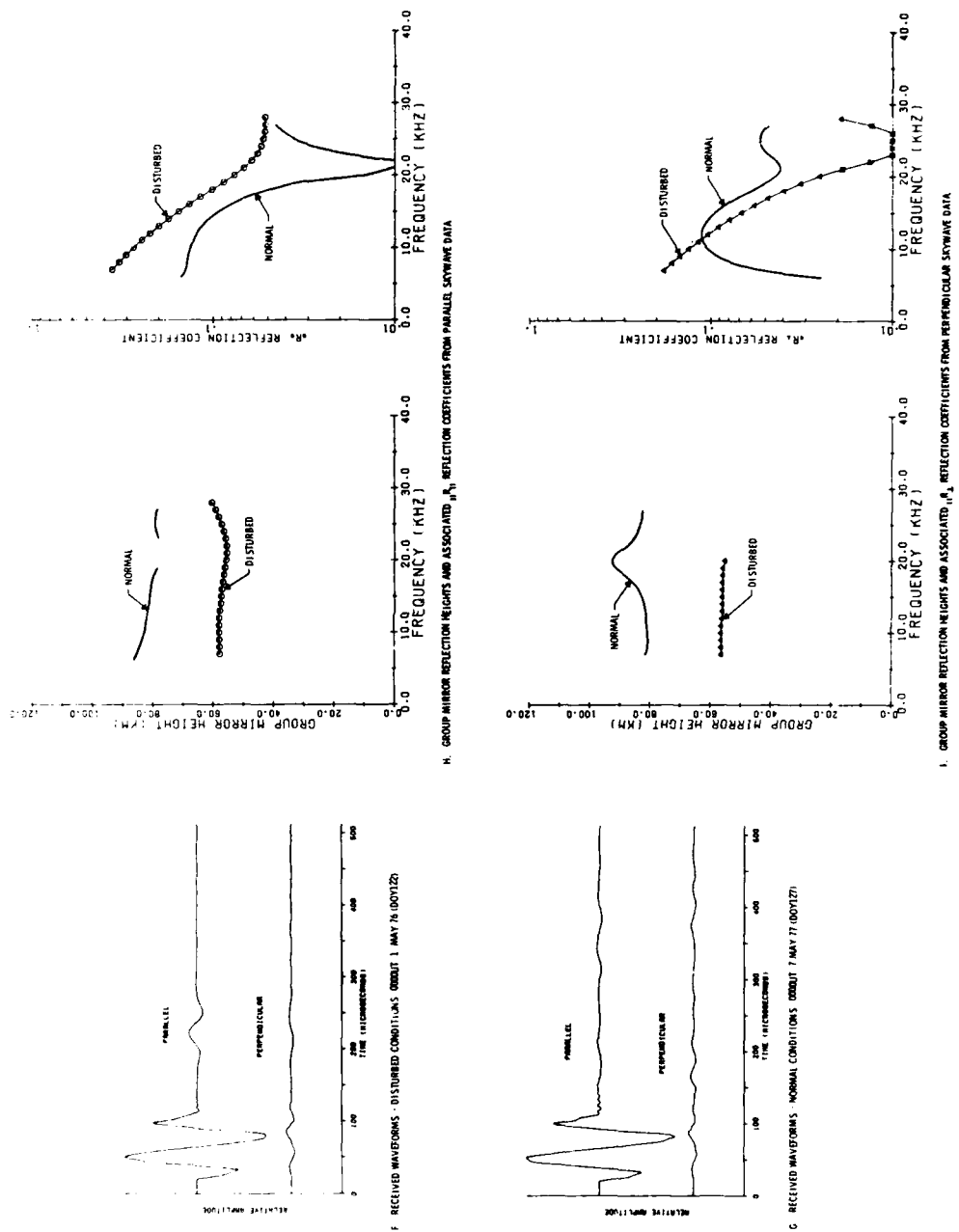
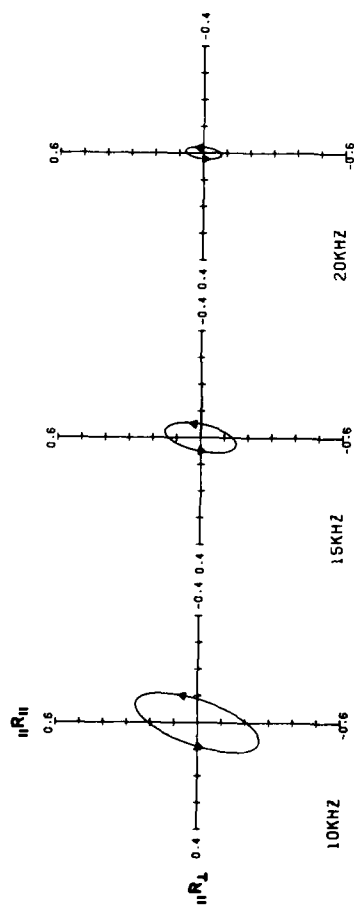
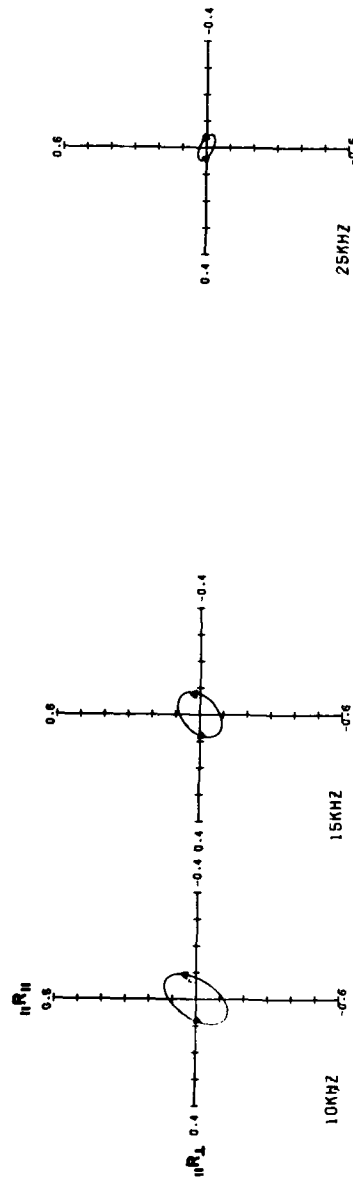


Figure 9. VLF/LF Ionospheric Reflectivity Data for 30 April 1976 (DOY 121) Solar Particle Event (continued)



J. SKYWAVE POLARIZATION ELLIPSES - DISTURBED CONDITIONS



K. SKYWAVE POLARIZATION ELLIPSES - NORMAL CONDITIONS

Figure 9. VLF/LF Ionospheric Reflectivity Data for 30 April 1976 (DOY 121) Solar Particle Event (continued)



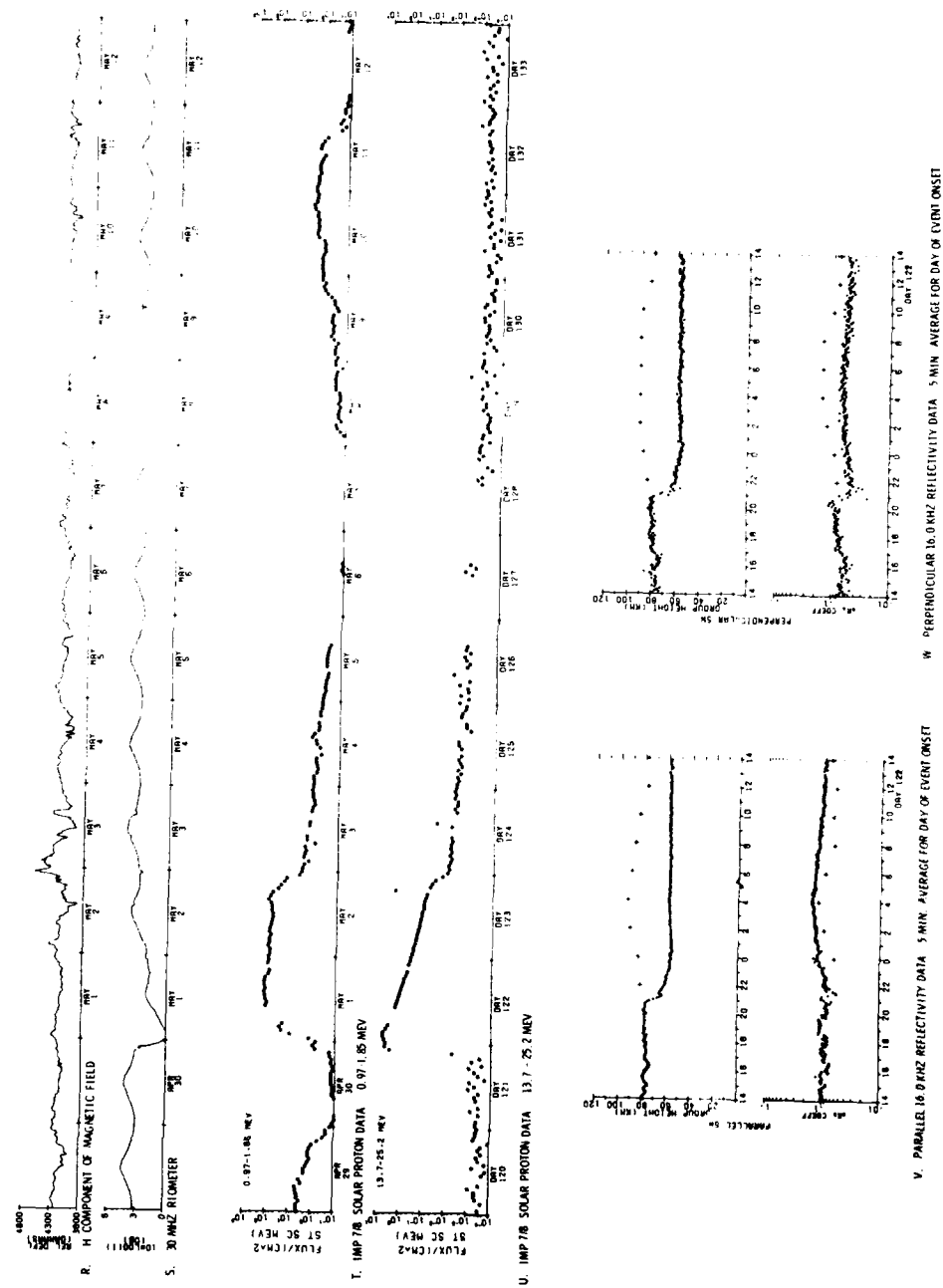


Figure 9. VLF/LF Ionospheric Reflectivity Data for 30 April 1976 (1000 121) Solar Particle Event (continued)



## 22 August 1976 Solar Particle Event

Date: 22 August 1976 DOY: 235  
Report Figure: 10  
Related Solar Flare: 22 August 1214 UT X-ray class: M3  
Start of Ionospheric Effects: 1230 UT  
Time of Maximum 13-25 MeV Proton Flux: 1300 UT  
Maximum Flux: 0.6 particles/cm<sup>2</sup> sr sec MeV  
Length of Particle Event: 3 days  
Lowest 16 kHz Reflection Height: 60 km  
Time of Lowest Reflection Height: 1600 UT  
30 MHz Riometer Absorption: 1.7 dB  
Solar Zenith Angle Range: 65°-93°  
Illumination Conditions: daytime

As with other polar daytime disturbance events, the  $R$  reflection coefficients at maximum particle flux (Part H) showed an increase for some frequencies and a decrease for other frequencies. After event maximum, the reflection coefficients were relatively steady for the next several days as compared with the coefficients *before and after the event* (Parts N and Q). In the latter part of the event, when the ionosphere had nearly recovered, the reflected skywave pulse became very weak for a period of about a day (Parts A and D). This same effect was seen in the April 1976 event (Figure 9). As seen in Parts N and Q on 24 August (DOY 237), the reflection coefficients were below the level at event maximum, particularly for 16 and 22 kHz. This again appears to be part of the disturbance recovery process rather than the result of an enhancement in the particle event itself. The reflection heights showed the usual daytime event pattern of an abrupt drop followed by a gradual recovery with no diurnal variations.

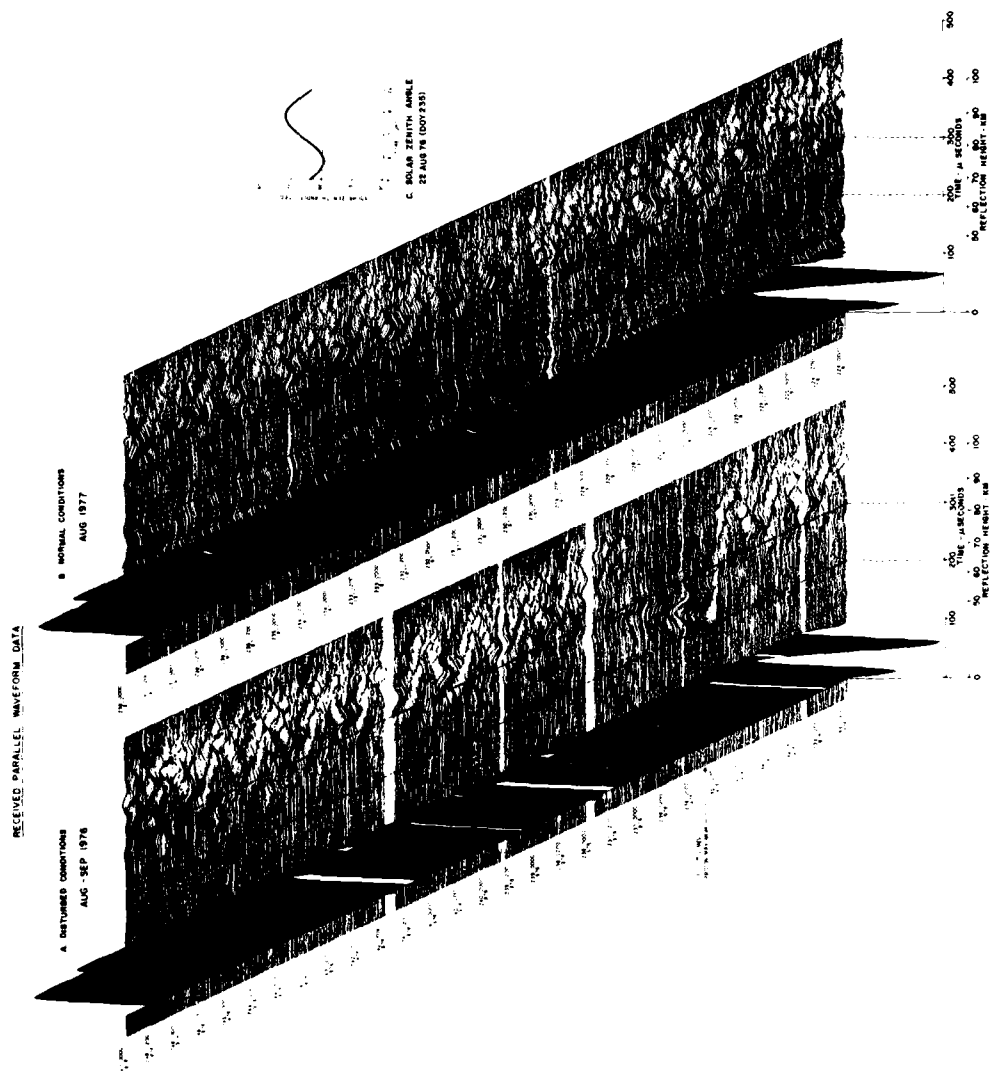


Figure 10. VLF/LF Ionospheric Reflectivity Data for 22 August 1976 (DOY 235) Solar Particle Event (continued)

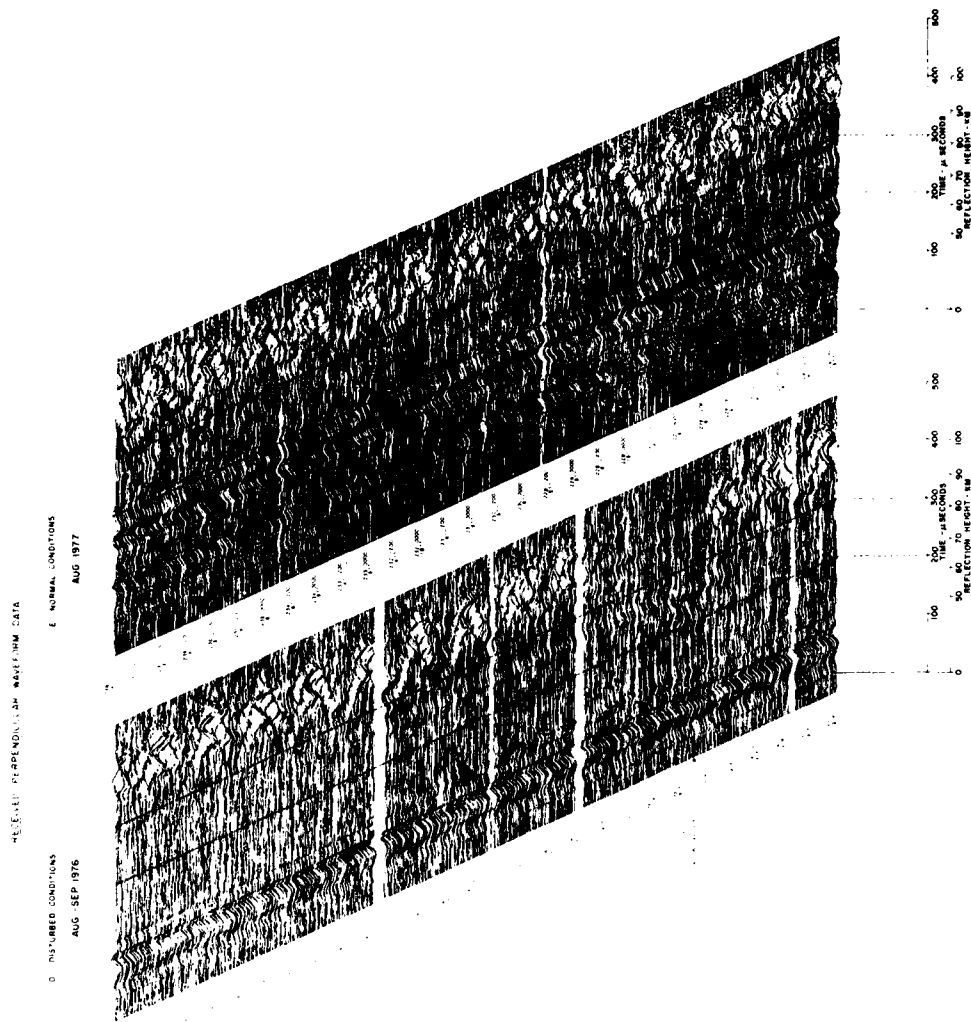


Figure 10. VLF/LF Ionospheric Reflectivity Data for 22 August 1976 (DOY 235) Solar Particle Event (continued)

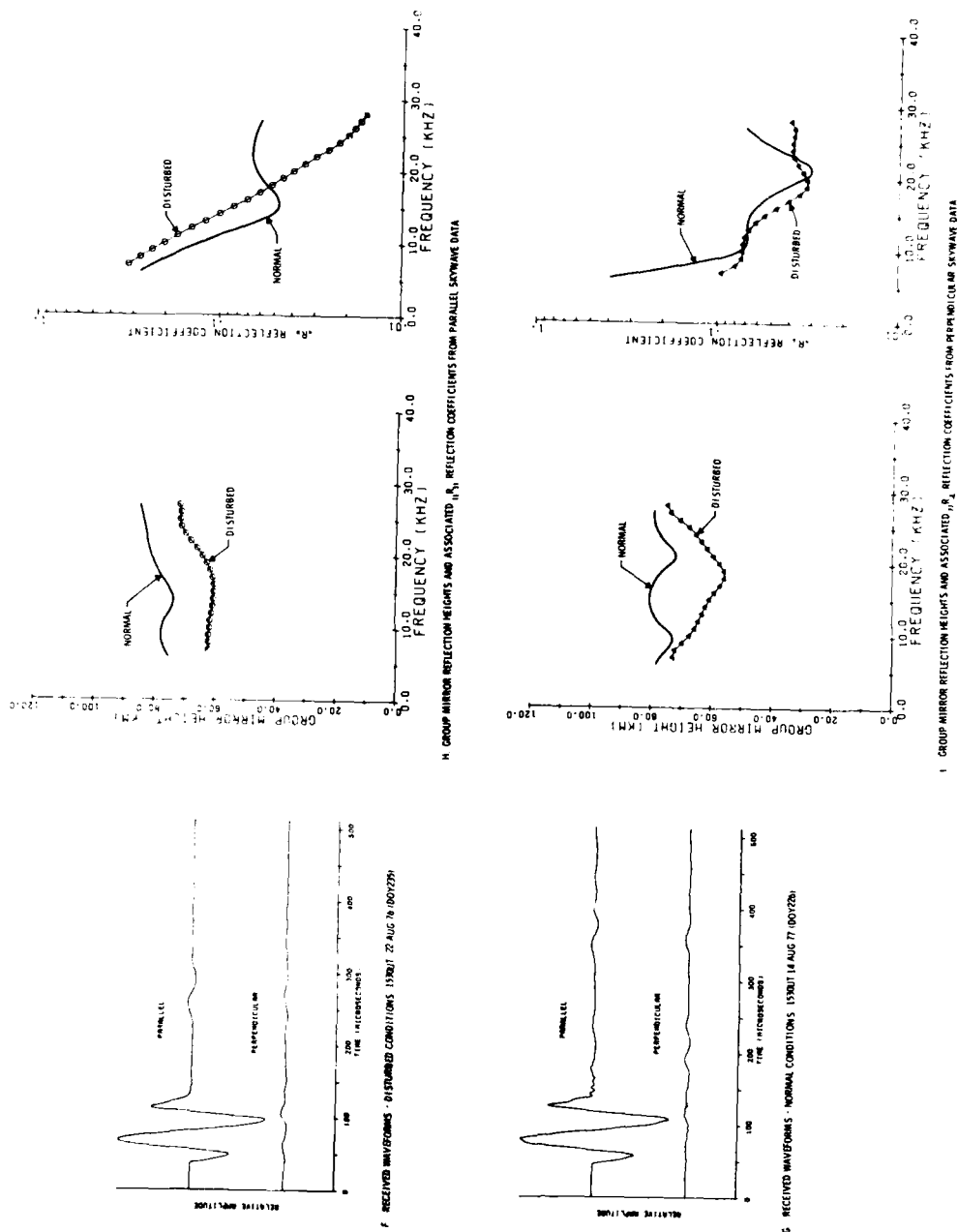
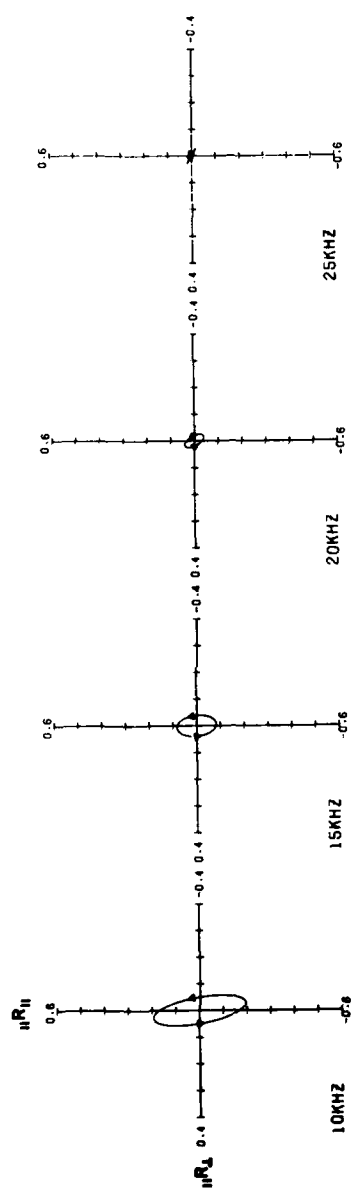
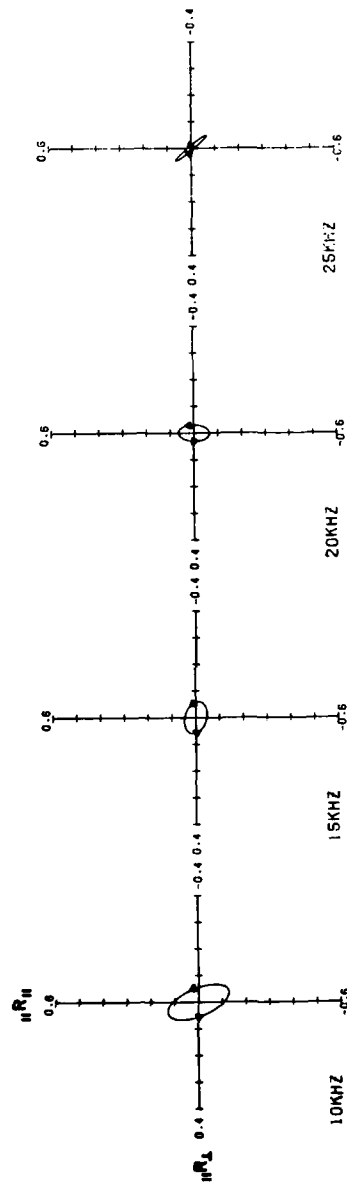


Figure 10. VLF/LF Ionospheric Reflectivity Data for 22 August 1976 (DOY 235) Solar Particle Event (continued)



J. SKYWAVE POLARIZATION ELLIPSES - DISTURBED CONDITIONS



K. SKYWAVE POLARIZATION ELLIPSES - NORMAL CONDITIONS

Figure 10. VLF/LF Ionospheric Reflectivity Data for 22 August 1976 (DOY 235) Solar Particle Event (continued)



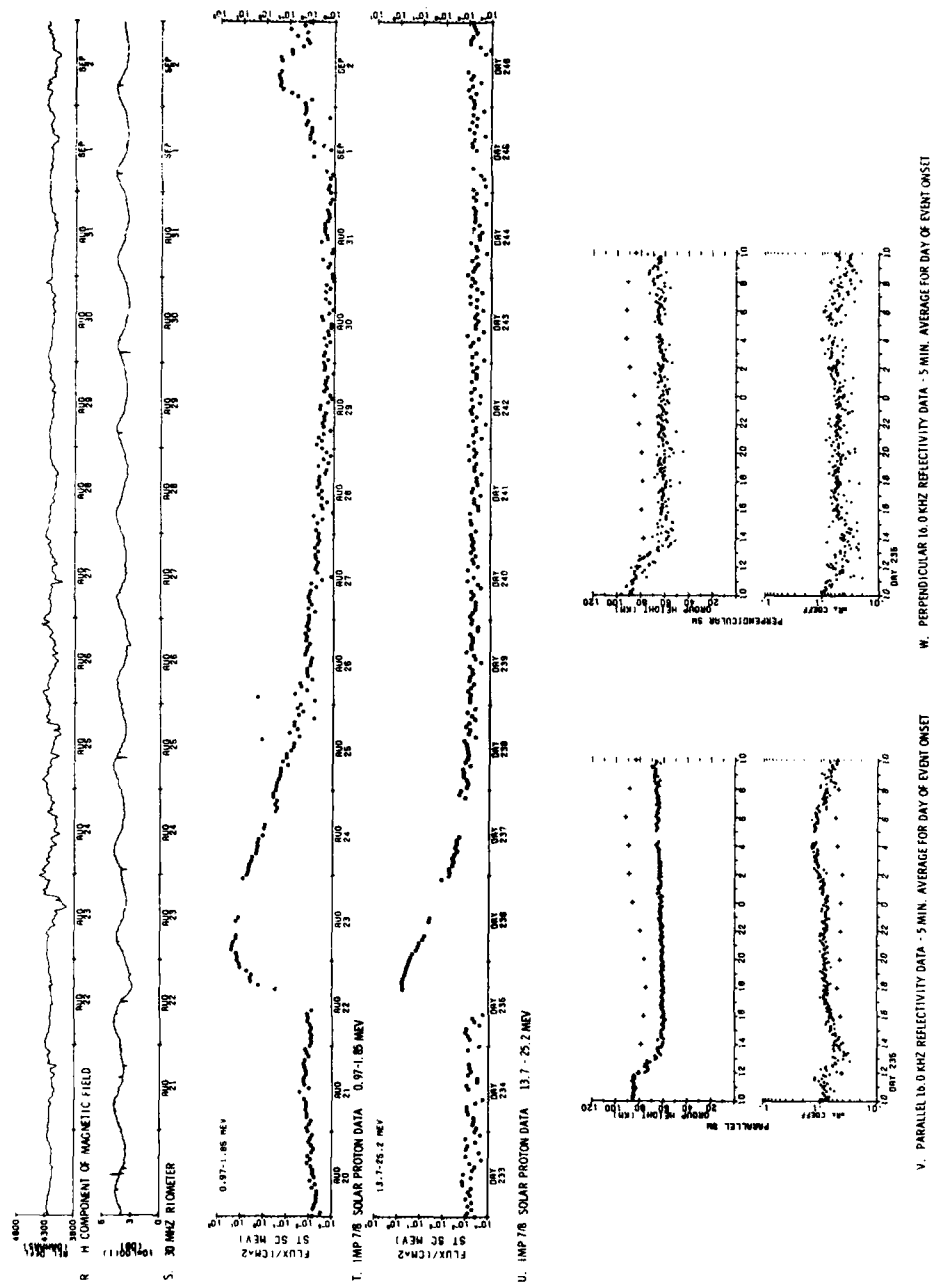


Figure 10. VLF/LF Ionospheric Reflectivity Data for 22 August 1976 (DOY 235) Solar Particle Event (continued)

# 26 July 1977 Solar Particle Event

Date: 26 July 1977    DOY: 207  
Report Figure: 11  
Related Solar Flare: No data  
Start of Ionospheric Effects: 1600 UT  
Time of Maximum 13-25 MeV Proton Flux: 2000 UT  
Maximum Flux: 0.02 particles/cm<sup>2</sup> sec sr MeV  
Length of Particle Event: 3 days  
Lowest 16 kHz Reflection Height: 70 km  
Time of Lowest Reflection Height: 0100 UT 27 July  
30 MHz Riometer Absorption: 0.5 dB  
Solar Zenith Angle Range: 58°-83°  
Illumination Conditions: daytime

This was the smallest particle event to be included in this report. Unlike other events reported here, the particle flux rose rather slowly to a maximum. As is typical of polar daytime events with continuous D-region illumination, the reflection height curves show a drop in height, followed by a gradual return to normal with no diurnal variation. The reflection coefficients which prior to the event were quite low and irregular, increased, and showed less variation during the event. The ionospheric reflection coefficients returned to normal by 29 July.



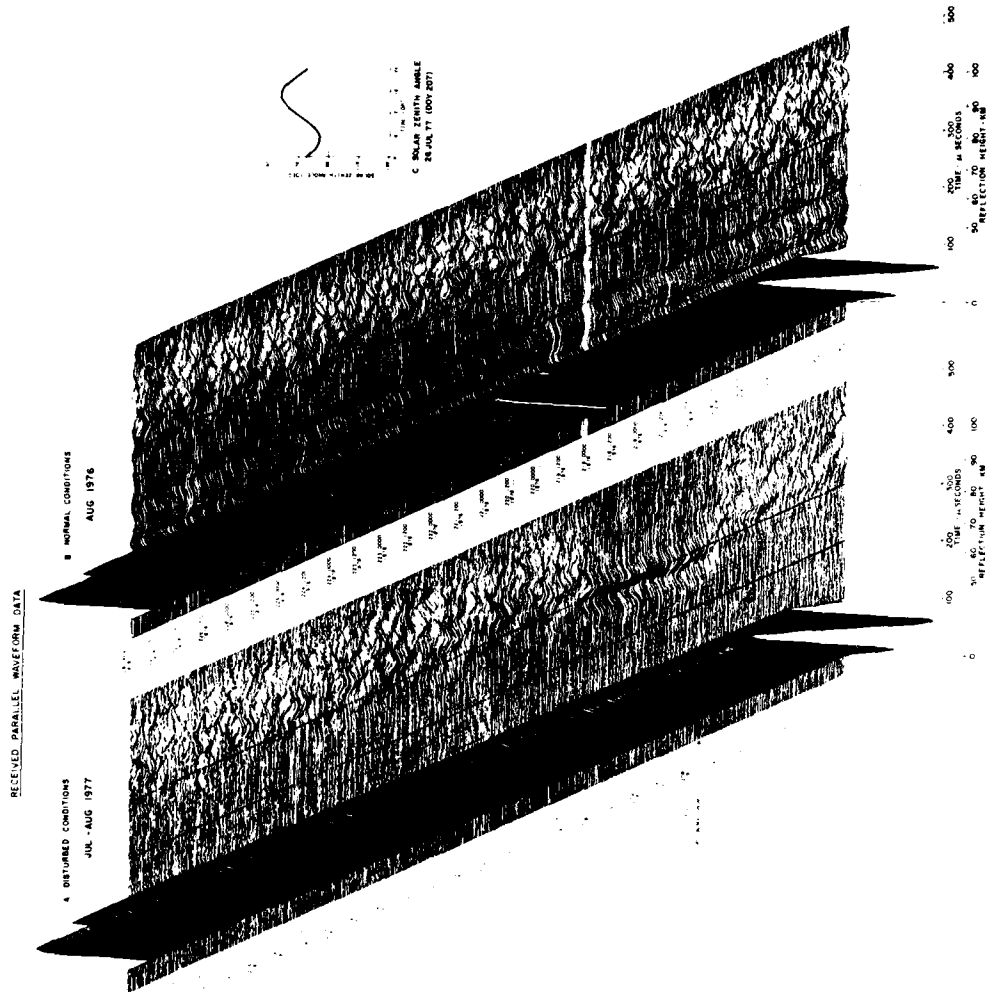


Figure 11. VLF/LF Ionospheric Reflectivity Data for 26 July 1977 (DOY 207) Solar Particle Event (continued)

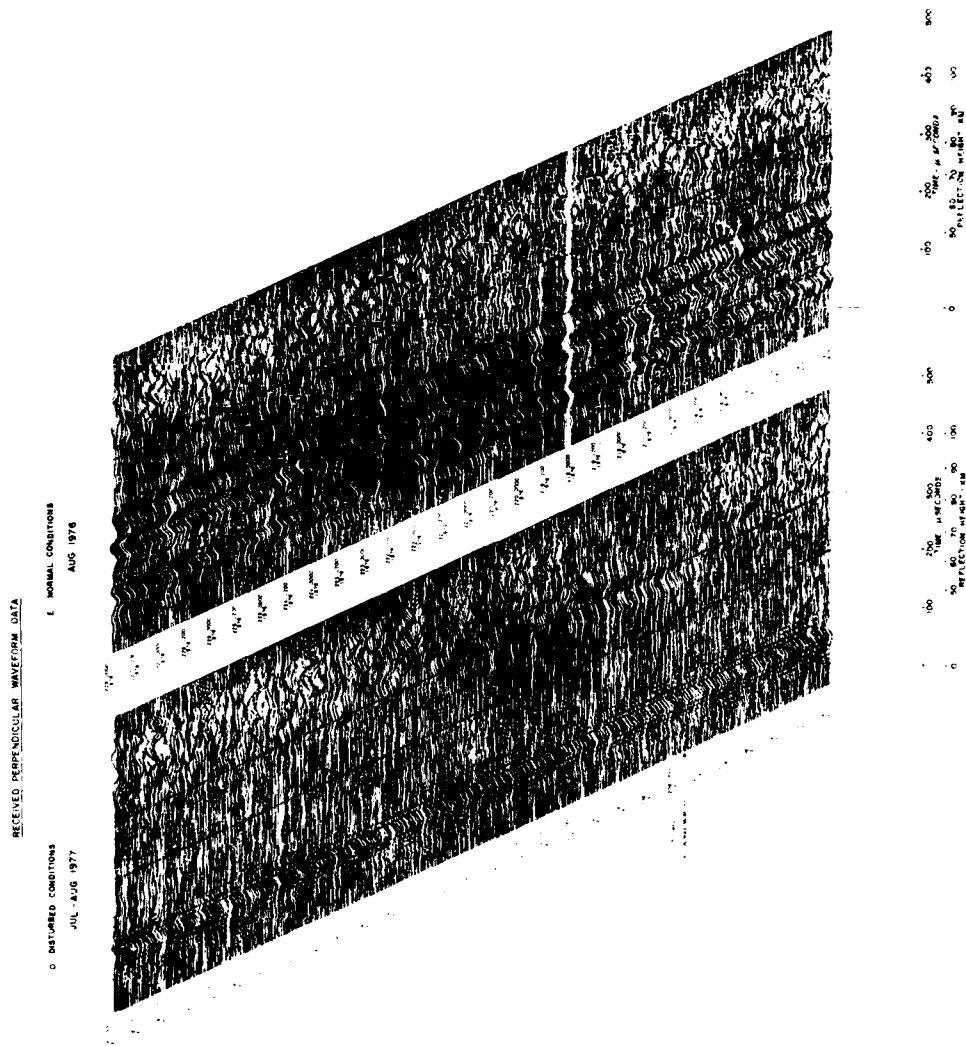


Figure 11. VLF/I.F. Ionospheric Reflectivity Data for 26 July 1977 (DOY 207) Solar Particle Event (continued)

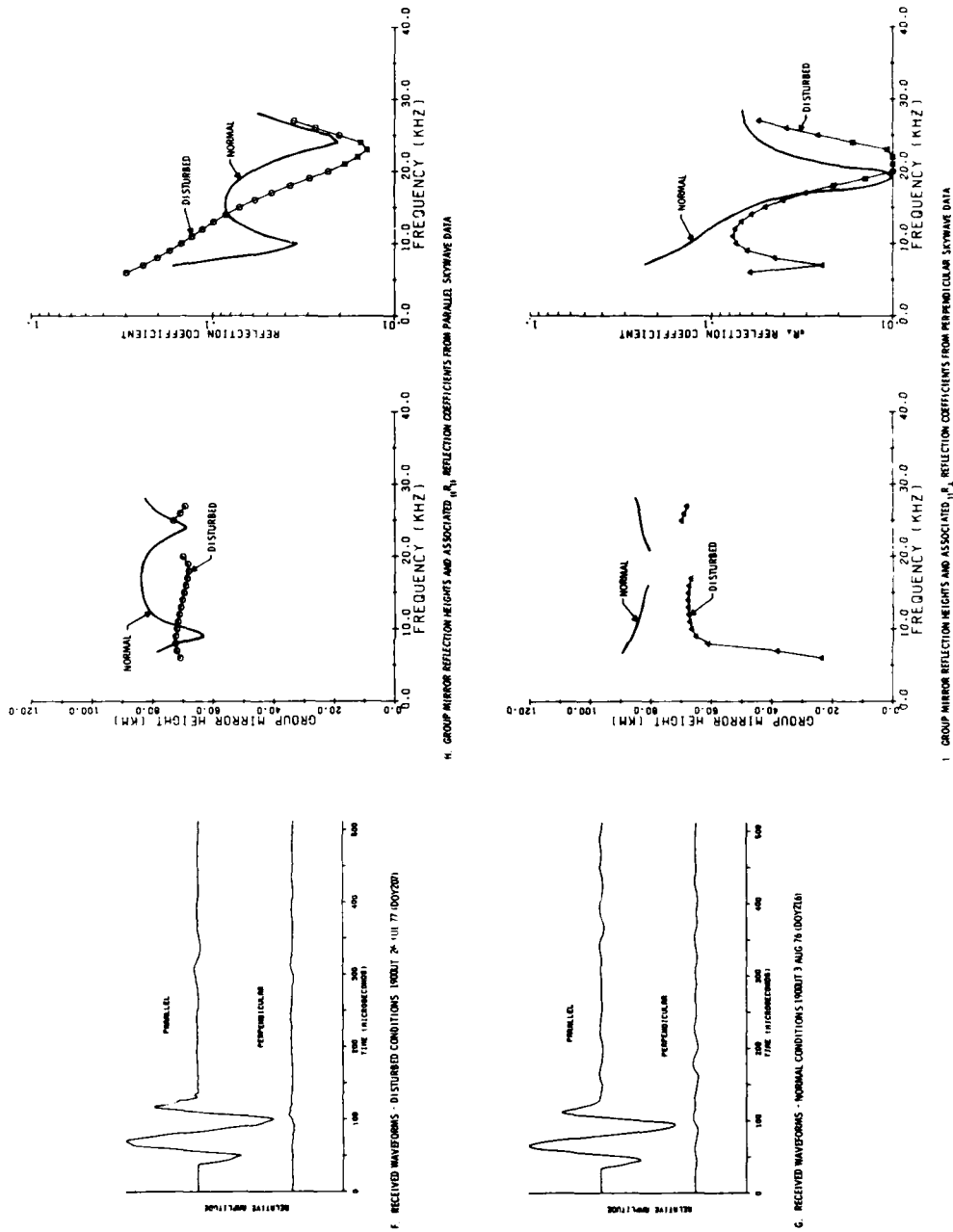
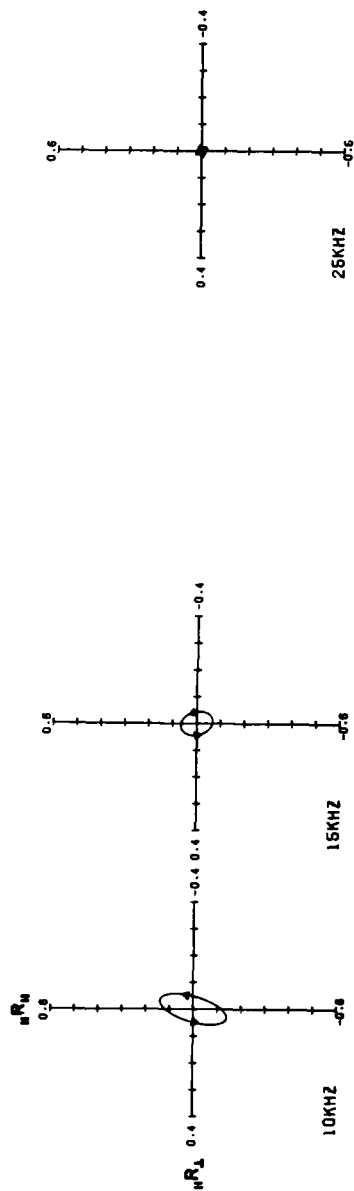
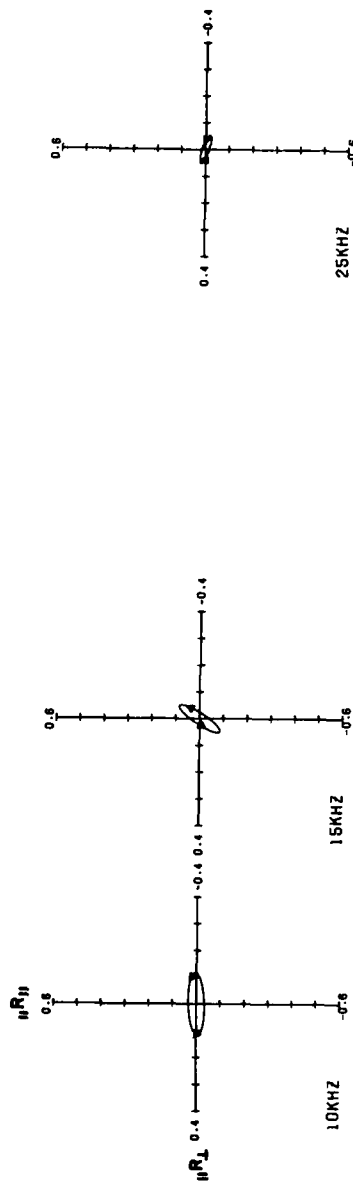


Figure 11. VLF/LF Ionospheric Reflectivity Data for 26 July 1977 (DOY 207) Solar Particle Event (continued)



J. SKYWAVE POLARIZATION ELLIPSES - DISTURBED CONDITIONS



K. SKYWAVE POLARIZATION ELLIPSES - NORMAL CONDITIONS

Figure 11. VLF/LF Ionospheric Reflectivity Data for 26 July 1977 (DOY 207) Solar Particle Event (continued)

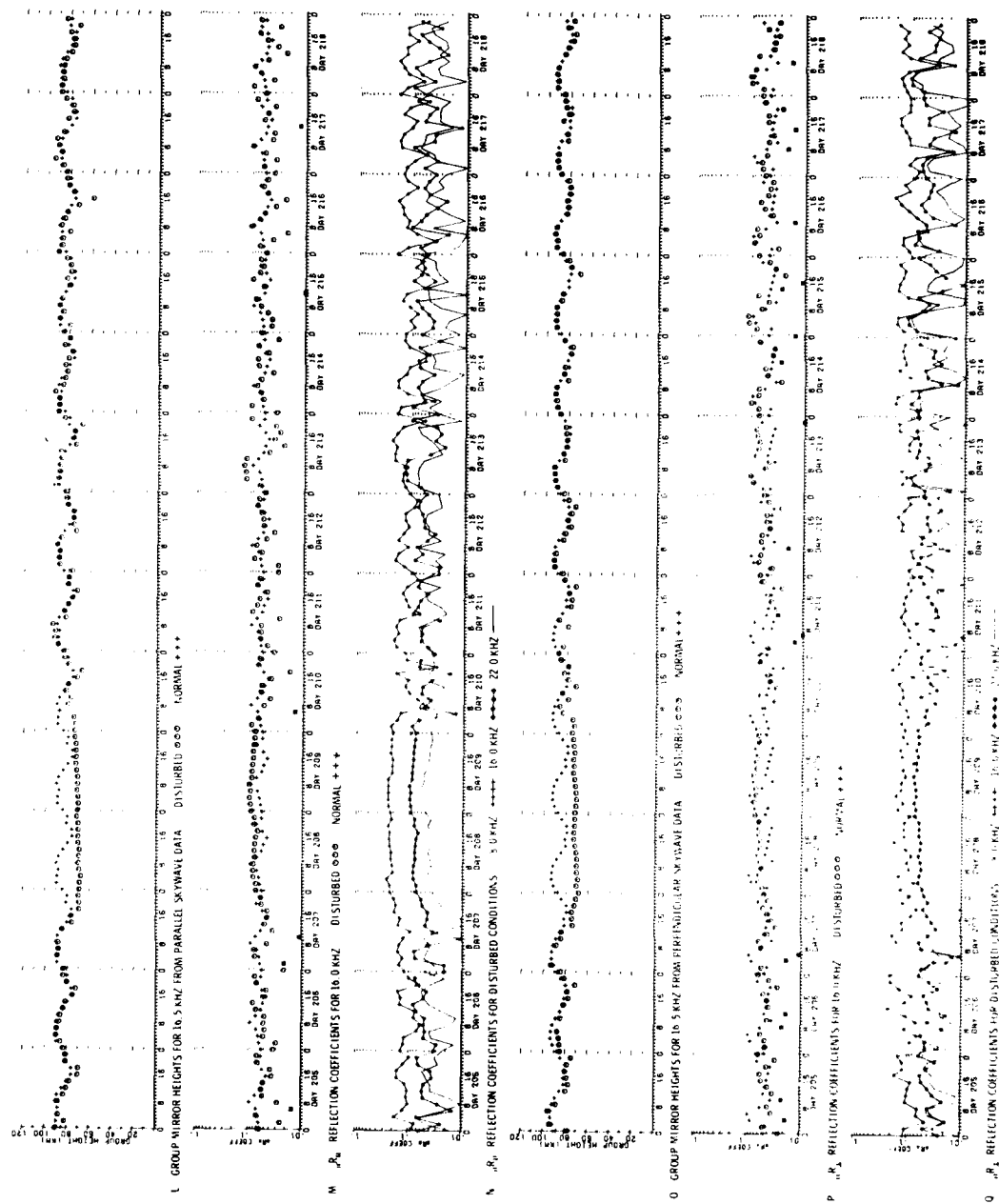


Figure 11. VLF/LF Ionospheric Reflectivity Data for 26 July 1977 (DOY 207) Solar Particle Event (continued)

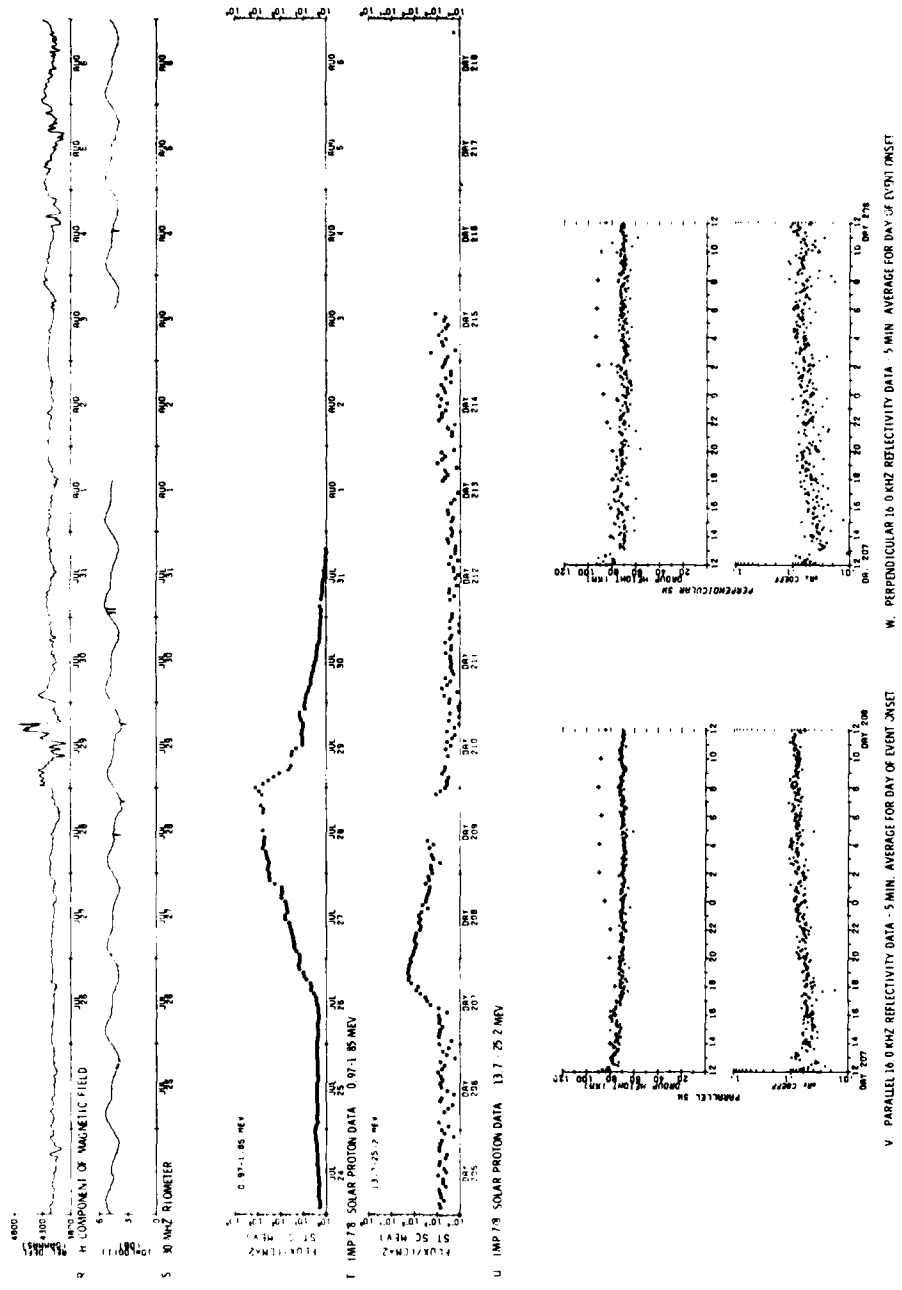


Figure 11. VLF/I/F Ionospheric Reflectivity Data for 26 July 1977 (DOY 207) Solar Particle Event (continued)

# 24 September 1977 Solar Particle Event

Date: 24 September 1977 DOY: 267  
Report Figure: 12  
Related Solar Flare: No data  
Start of Ionospheric Effects: 0615 UT  
Time of Maximum 13-25 MeV Proton Flux: 1000 UT  
Maximum Flux: 2 particles/cm<sup>2</sup> sec sr MeV  
Length of Particle Event: 6 days  
Lowest 16 kHz Reflection Height: 57 km  
Time of Lowest Reflection Height: 1400 UT  
30 MHz Riometer Absorption: 2 dB  
Solar Zenith Angle Range: 75°-103°  
Illumination Conditions: Day-night

This energetic particle event occurred during an already disturbed period; a series of events had occurred, beginning on 8 September (DOY 251). No data are presented for these events as ionosounding records are incomplete. This was a day-night event with the sun rising and setting. Unlike polar daytime or nighttime events, there was an enhanced diurnal variation of the reflection heights and coefficients during the event. Solar radiation and particle ionization resulted in lower noontime reflection heights; the absence of solar radiation at night allowed the recombination of electrons, and thus a partial recovery toward normal reflection height conditions.

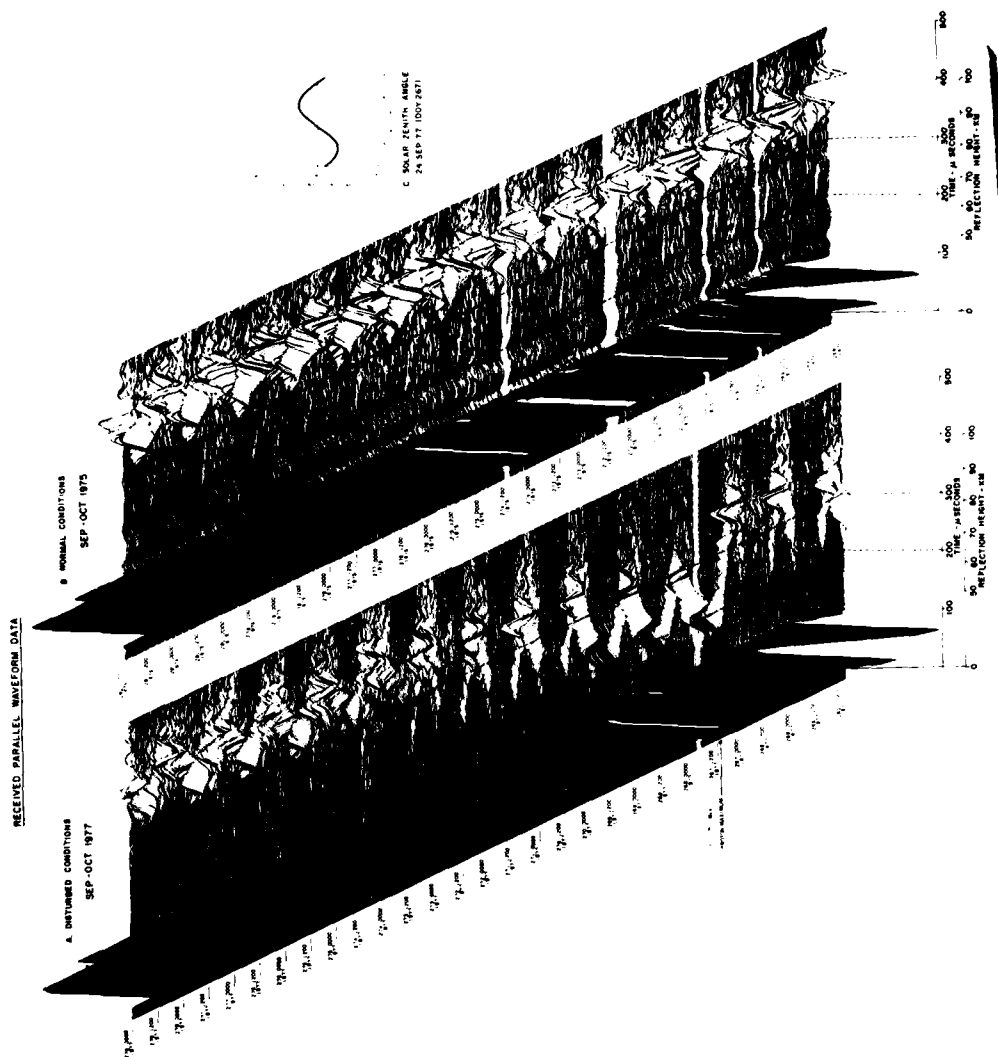


Figure 12. VLF/LF Ionospheric Reflectivity Data for 24 September 1977 (Data from [unclear] Event (continued))



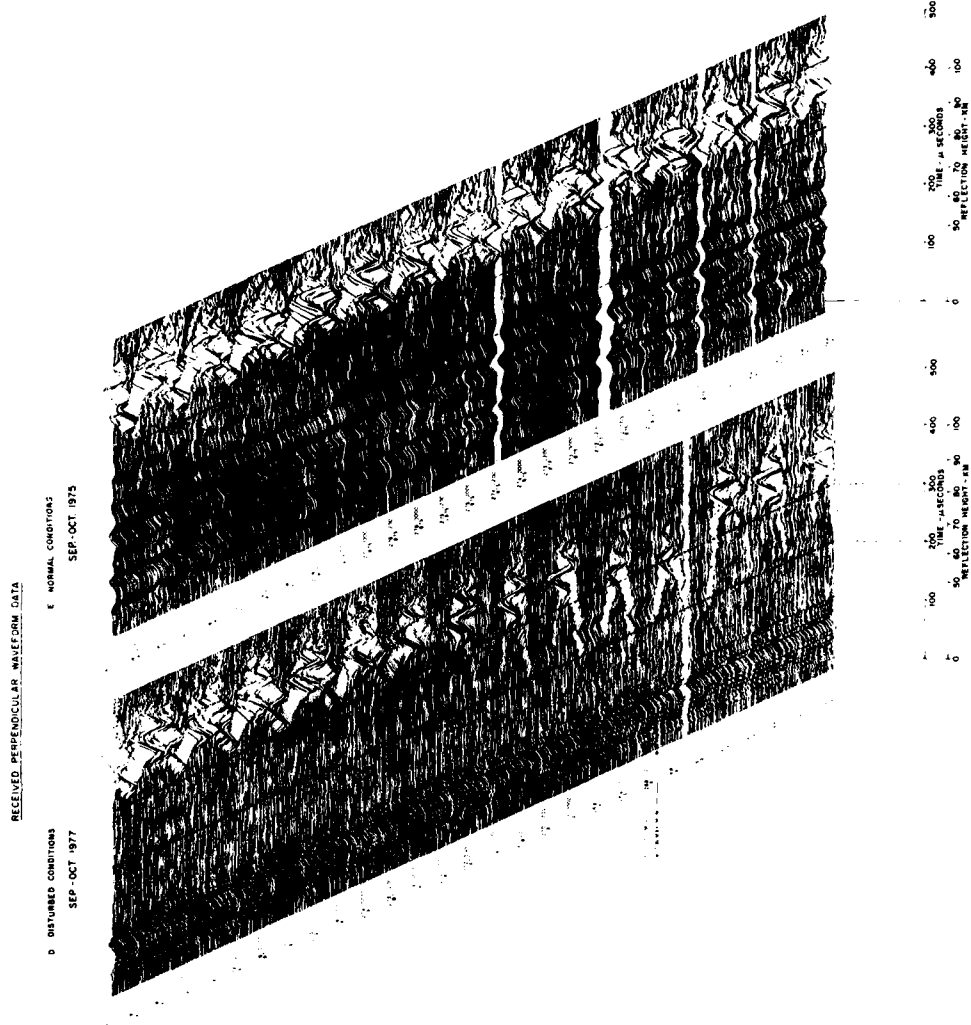


Figure 12. VLF/LF Ionospheric Reflectivity Data for 24 September 1977 (DOY 267) Solar Particle Event (continued)

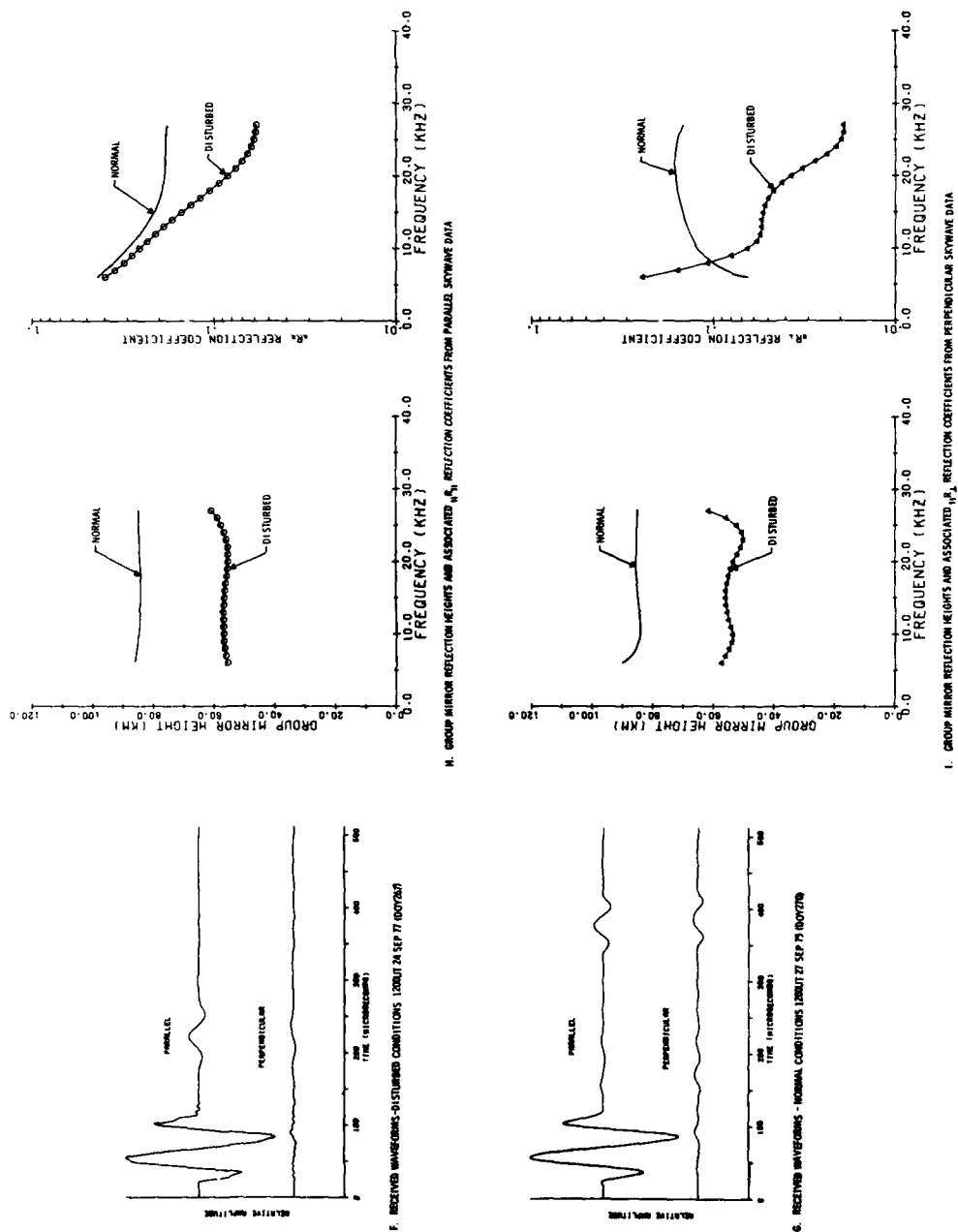
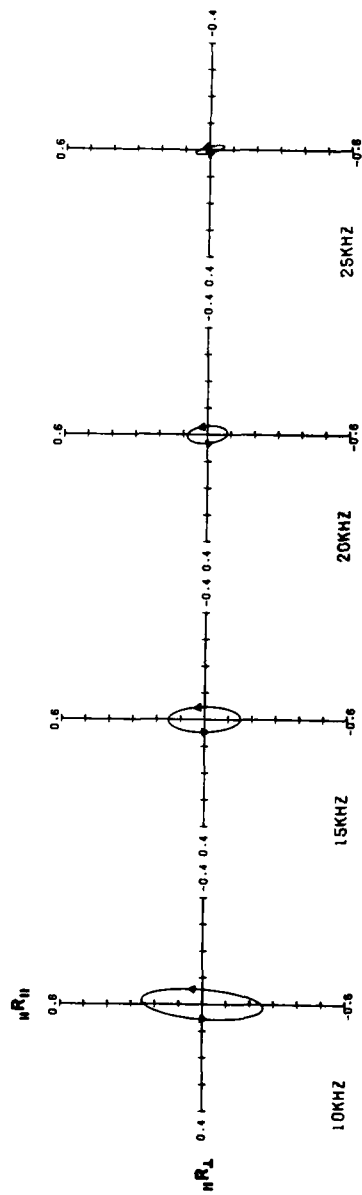
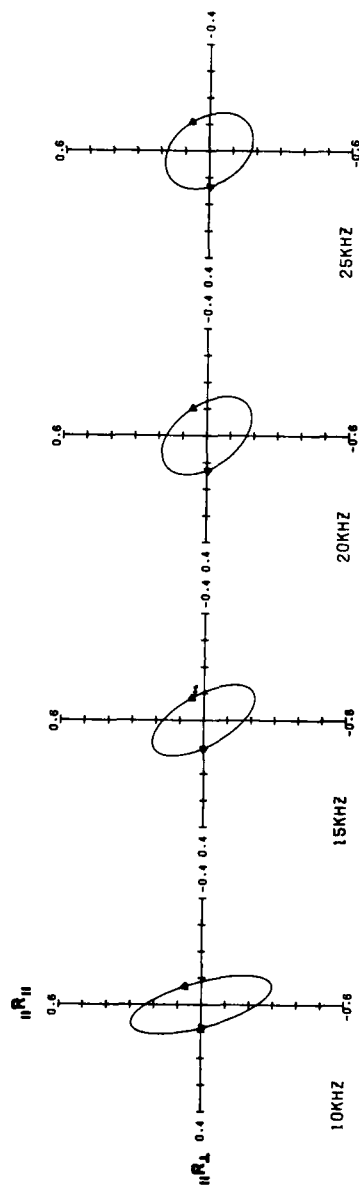


Figure 12. VLF/LF Ionospheric Reflectivity Data for 24 September 1977 (DOY 267) Solar Particle Event (continued)



J. SKYWAVE POLARIZATION ELLIPSES - DISTURBED CONDITIONS



K. SKYWAVE POLARIZATION ELLIPSES - NORMAL CONDITIONS

Figure 12. VLF/LF Ionospheric Reflectivity Data for 24 September 1977 (DOY 267) Solar Particle Event (continued)



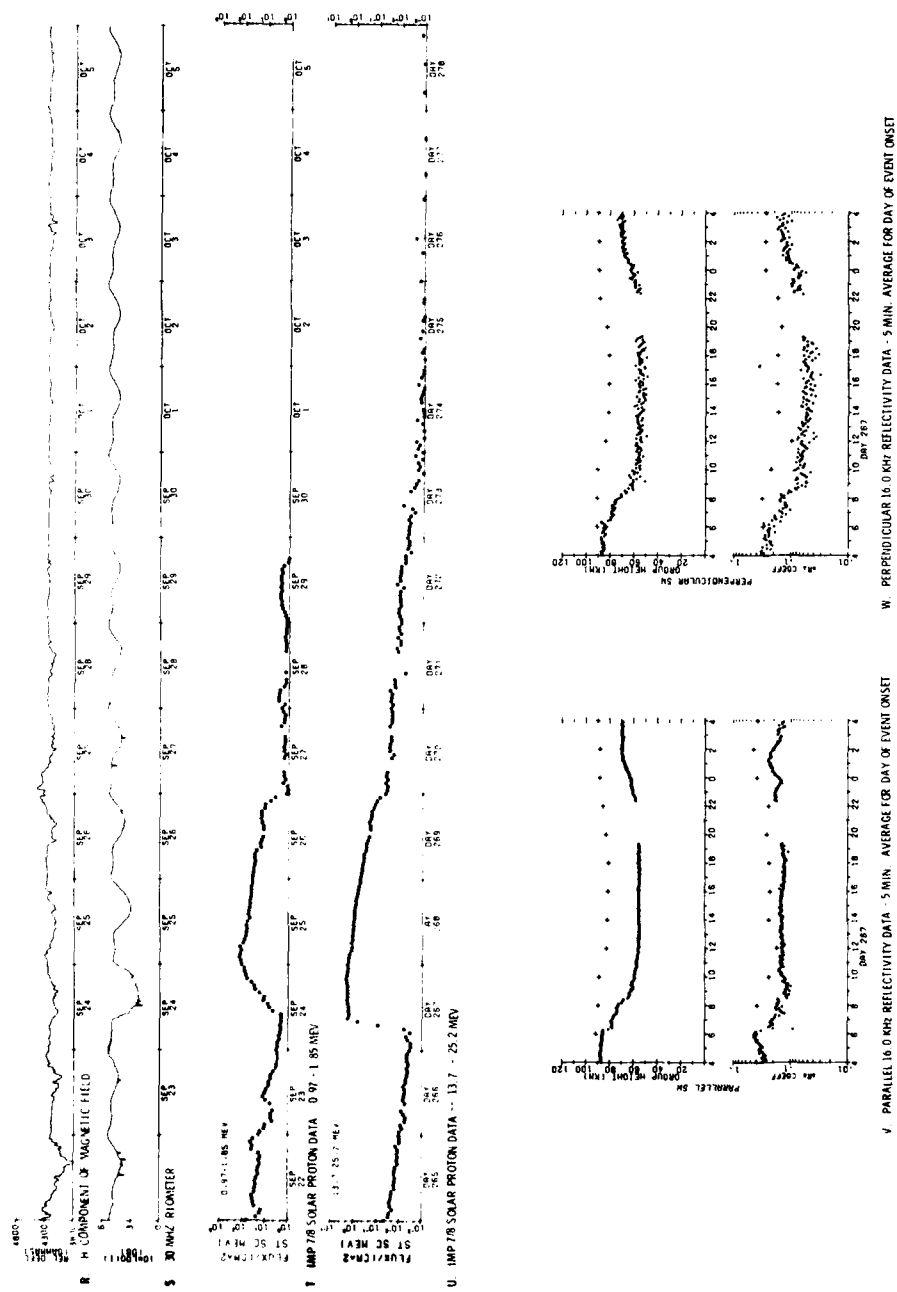


Figure 12. VLF/LF Ionospheric Reflectivity Data for 24 September 1977 (DOY 267) Solar Particle Event (continued)

## 22 November 1977 Solar Particle Event

Date: 22 November 1977    DOY: 326  
Report Figure: 13  
Related Solar Flare: 0945 UT    x-ray class: X1  
Start of Ionospheric Effects: 1030 UT  
Time of Maximum 13-25 MeV Proton Flux: 1600 UT  
Maximum Flux: 14 particles/cm<sup>2</sup> sec sr MeV  
Length of Particle Event: 8 days  
Lowest 16 kHz Reflection Height: 64  
Time of Lowest Reflection Height: 1700 UT  
30 MHz Riometer Absorption: 0.75 dB  
Solar Zenith Angle Range: 96°-124°  
Illumination Conditions: nighttime

Based on the high energy proton flux, this was the strongest event during the period of this report. Because this was a polar nighttime event, however, the magnitude of the effects on the VLF/LF parameters was less than would have occurred had there been solar illumination. The daytime 20 August 1976 event with only 0.6 particles/cm<sup>2</sup> sec sr MeV produced a lower reflection height of about 60 km. As is typical of a nighttime event, the disturbance effects on the reflection heights and coefficients (Parts L-Q) are well defined: an abrupt drop followed by a gradual recovery basically following the particle flux curve.



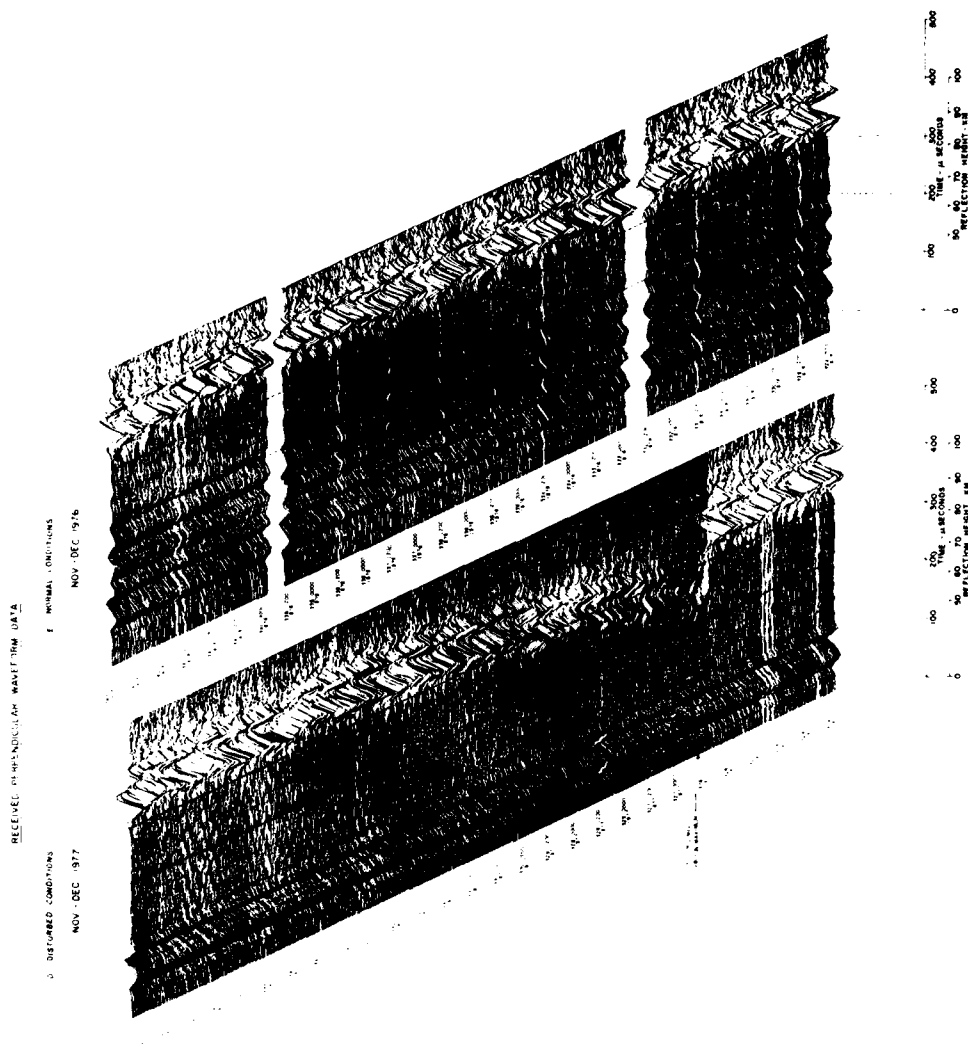


Figure 13. VLF/LF Ionospheric Reflectivity Data for 22 November 1977 (DOY 326) Solar Particle Event (continued)



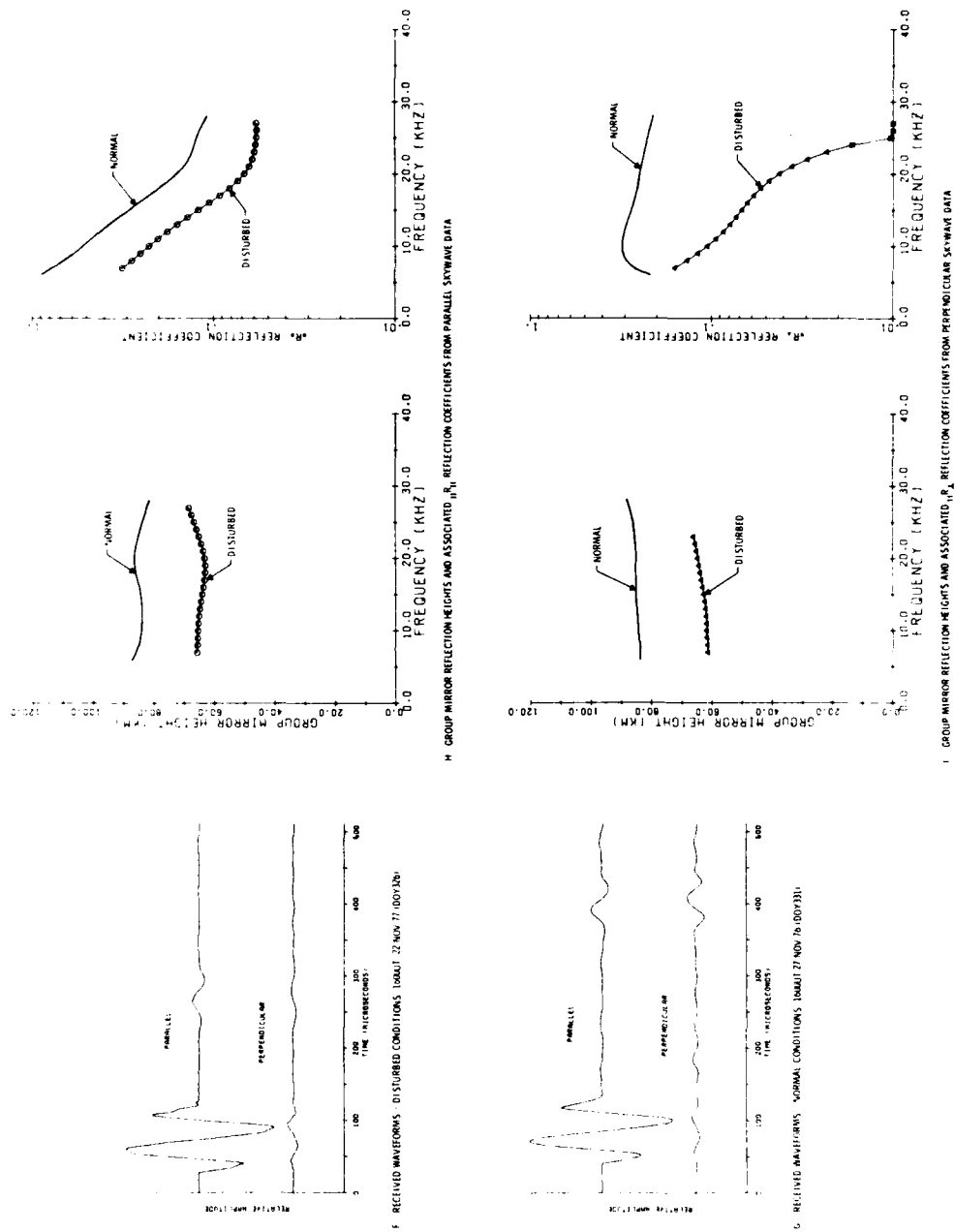
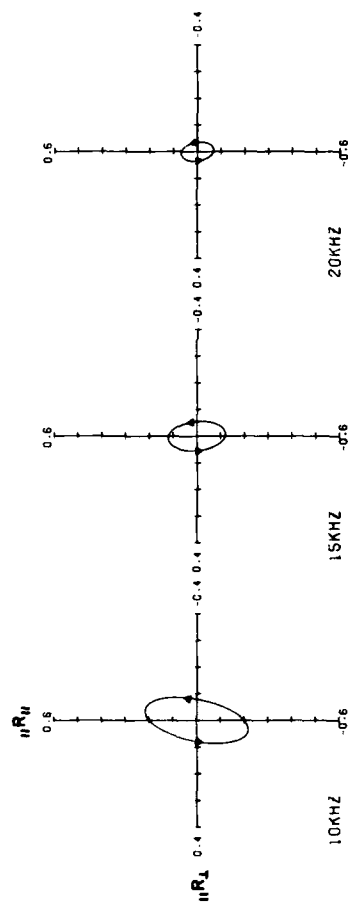
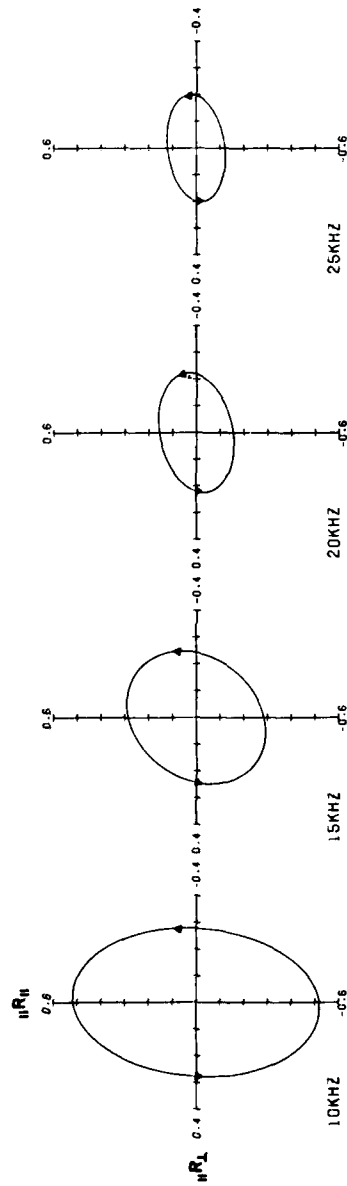


Figure 13. VLF/LF Ionospheric Reflectivity Data for 22 November 1977 (DOY 326) Solar Particle Event (continued)



J. SKYWAVE POLARIZATION ELLIPSES - DISTURBED CONDITIONS



K. SKYWAVE POLARIZATION ELLIPSES - NORMAL CONDITIONS

Figure 13. VLF/LF Ionospheric Reflectivity Data for 22 November 1977 (DOY 326) Solar Particle Event (continued)

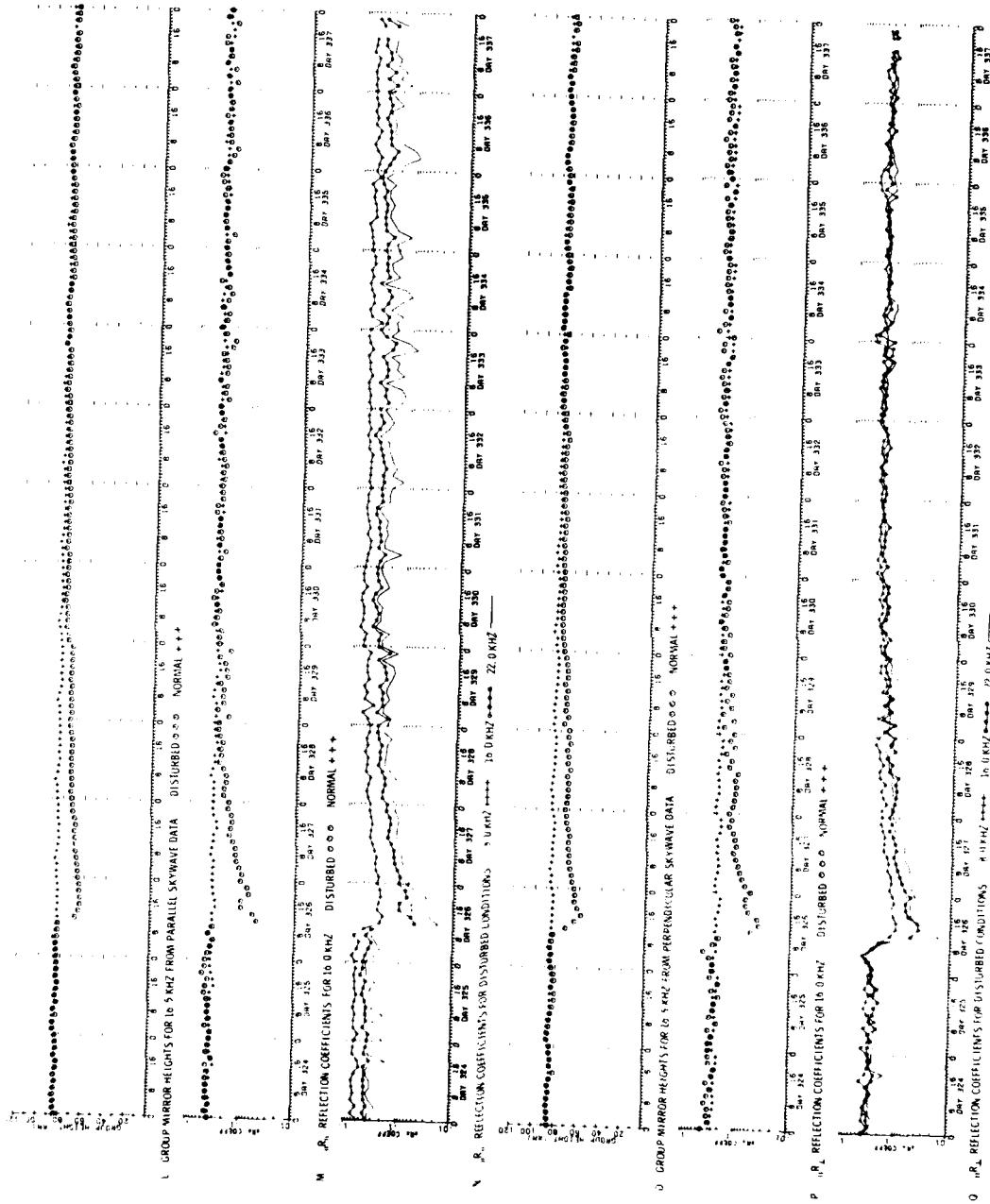


Figure 13. VLF/LF Ionospheric Reflectivity Data for 22 November 1977 (DOY 326) Solar Particle Event (continued)

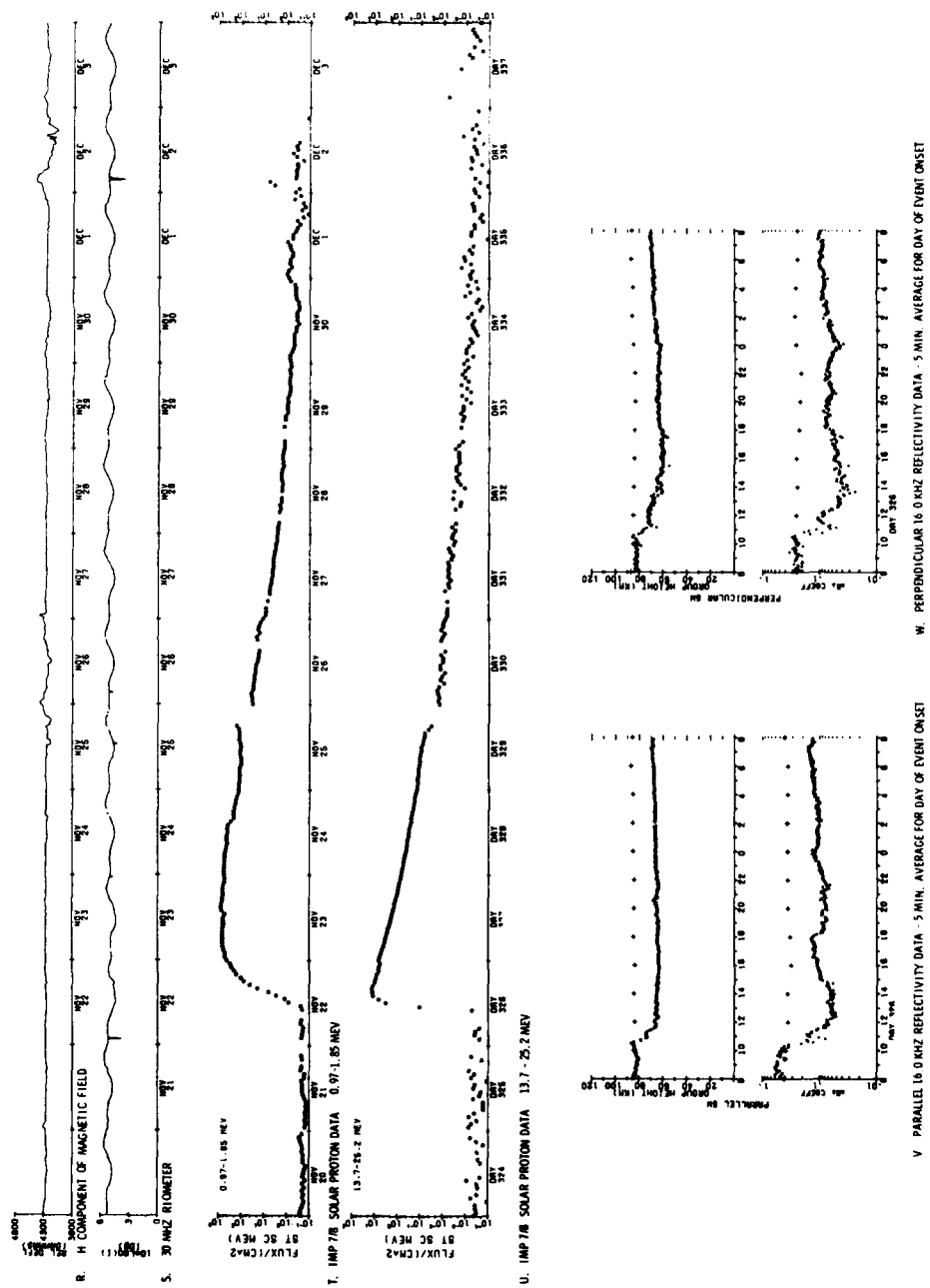


Figure 13. VLF/LF Ionospheric Reflectivity Data for 22 November 1977 (DOY 326) Solar Particle Event (continued)

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